Attorney Case No. 108-103USA000

METHOD OF AND SYSTEM FOR ACQUIRING AND ANALYZING INFORMATION ABOUT THE PHYSICAL ATTRIBUTES OF OBJECTS USING PLANAR LASER ILLUMINATION BEAMS, VELOCITY-DRIVEN AUTO-FOCUSING AND AUTO-ZOOM IMAGING OPTICS, AND HEIGHT AND VELOCITY CONTROLLED IMAGE DETECTION ARRAYS

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CROSS-REFERENCE TO RELATED U.S. APPLICATIONS

This is a Continuation-in-Part of copending Application Serial No. 09/---,--- entitled " Method Of And System For Producing Images Of Objects Using Planar Laser Illumination Beams And Image Detection Arrays" filed February 9, 2001 under 37 C.F.R. 1.10 (Express Mail No. EL701906489US); copending Application Serial No. 09/721,885 filed November 24, 2000; International Application PCT/US99/06505 filed March 24, 1999, published as WIPO WO 99/49411; International Application PCT/US99/28530 filed December 2, 1999, published as WIPO Publication WO 00/33239; International Application PCT/US00/15624 filed June 7, 2000, published as WIPO Publication WO 00/75856; copending Application Serial No. 09/452,976 filed December 2, 1999; Application Serial No. 09/327,756 filed June 7, 1999, which is a Continuation-in-Part of Application Serial No. 09/305,896 filed May 5, 1999, which is a Continuation-in-Part of copending Application No. 09/275,518 filed March 24, 1999, which is a Continuation-in-Part of copending Application Nos.: 09/274,265 filed March 22, 1999; 09/243,078 filed February 2, 1999; 09/241,930 filed February 2, 1999; 09/157,778 filed September 21, 1998; 09/047,146 filed March 24, 1998, 08/949,915 filed October 14, 1997, now U.S. Letters Patent 6,158,659; 08/854,832 filed May 12, 1997, now U.S. Letters Patent 6,085,978; 08/886,806 filed April 22, 1997, now U.S. Letters Patent 5,984,185; 08/726,522 filed October 7, 1996, now U.S. Letters Patent 6,073,846; 08/573,949 filed December 18, 1995, now abandoned; each said application being commonly owned by Assignee, Metrologic Instruments, Inc., of Blackwood, New Jersey, and incorporated herein by reference as if fully set forth herein.

BACKGROUND OF THE INVENTION

Field of Invention

The present invention relates generally to an improved method of and system for illuminating moving and well as stationary objects, such as parcels, during image formation and detection operations, and also to an improved method of and system for acquiring and analyzing information about the physical attributes of such objects using such improved methods of object illumination, and digital image analysis.

<u>Brief Description Of The State Of Knowledge In The Art</u>

The use of image-based bar code symbol readers and scanners is well known in the field of auto-identification. Examples of image-based bar code symbol reading/scanning systems include, for example, hand-hand scanners, point-of-sale (POS) scanners, and industrial-type conveyor scanning systems.

Presently, most commercial image-based bar code symbol readers are constructed using charge-coupled device (CCD) image sensing/detecting technology. Unlike laser-based scanning technology, CCD imaging technology has particular illumination requirements which differ from application to application.

Most prior art CCD-based image scanners, employed in conveyor-type package identification systems, require high-pressure sodium, metal halide or halogen lamps and large, heavy and expensive parabolic or elliptical reflectors to produce sufficient light intensities to illuminate the large depth of field scanning fields supported by such industrial scanning systems. Even when the light from such lamps is collimated or focused using such reflectors, light strikes the target object other than where the imaging optics of the CCD-based camera are viewing. Since only a small fraction of the lamps output power is used to illuminate the CCD camera's field of view, the total output power of the lamps must be very high to obtain the illumination levels required along the field of view of the CCD camera. The balance of the output illumination power is simply wasted in the form of heat.

Most prior art CCD-based hand-held image scanners use an array of light emitting diodes (LEDs) to flood the field of view of the imaging optics in such scanning systems. A large percentage of the output illumination from these LED sources is dispersed to regions other than the field of view of the scanning system. Consequently, only a small percentage of the illumination is actually collected by the imaging optics of the system, Examples of prior art CCD hand-held image scanners employing LED illumination arrangements are disclosed in US Patent Nos. Re. 36,528, 5,777,314, 5,756,981, 5,627,358, 5,484,994, 5,786,582, and 6,123,261 to Roustaei, each assigned to Symbol Technologies, Inc. and incorporated herein by reference in its entirety. In such prior art CCD-based hand-held image scanners, an array of LEDs are mounted in a scanning head in front of a CCD-based image sensor that is provided with a cylindrical lens assembly. The LEDs are arranged at an angular orientation relative to a central axis passing through the scanning head so that a fan of light is emitted through the light transmission aperture thereof that expands with increasing distance away from the LEDs. The intended purpose of this LED illumination arrangement is to increase the "angular distance" and "depth of field" of CCD-based bar code symbol readers. However, even with such improvements in LED illumination techniques, the working distance of such hand-held CCD

scanners can only be extended by using more LEDs within the scanning head of such scanners to produce greater illumination output therefrom, thereby increasing the cost, size and weight of such scanning devices.

Similarly, prior art "hold-under" and "hands-free presentation" type CCD-based image scanners suffer from shortcomings and drawbacks similar to those associated with prior art CCD-based hand-held image scanners.

Recently, there have been some technological advances made involving the use of laser illumination techniques in CCD-based image capture systems to avoid the shortcomings and drawbacks associated with using sodium-vapor illumination equipment, discussed above. In particular, US Patent No. 5,988,506 (assigned to Galore Scantec Ltd.), incorporated herein by reference, discloses the use of a cylindrical lens to generate from a single visible laser diode (VLD) a narrow focused line of laser light which fans out an angle sufficient to fully illuminate a code pattern at a working distance. As disclosed, mirrors can be used to fold the laser illumination beam towards the code pattern to be illuminated in the working range of the system. Also, a horizontal linear lens array consisting of lenses is mounted before a linear CCD image array, to receive diffused reflected laser light from the code symbol surface. Each single lens in the linear lens array forms its own image of the code line illuminated by the laser illumination beam. Also, subaperture diaphragms are required in the CCD array plane to (i) differentiate image fields, (ii) prevent diffused reflected laser light from passing through a lens and striking the image fields of neighboring lenses, and (iii) generate partially-overlapping fields of view from each of the neighboring elements in the lens array. However, while avoiding the use of external sodium vapor illumination equipment, prior art laser-illuminated CCD-based image capture system suffers from several significant shortcomings and drawbacks. In particular, it requires very complex image forming optics which makes this system design difficult and expensive to manufacture, and imposes a number of undesirable constraints which are very difficult to satisfy when constructing an auto-focus/auto-zoom image acquisition and analysis system for use in demanding applications.

Thus, there is a great need in the art for an improved method of and system for illuminating the surface of objects during image formation and detection operations, and also an improved method of and system for producing digital images using such improved methods object illumination, while avoiding the shortcomings and drawbacks of prior art illumination, imaging and scanning systems and methodologies.

OBJECTS AND SUMMARY OF THE PRESENT INVENTION

Accordingly, a primary object of the present invention is to provide an improved method of and system for illuminating the surface of objects during image formation and detection operations and also improved methods of and systems for producing digital images using such improved methods object illumination, while avoiding the shortcomings and drawbacks of prior art systems and methodologies.

Another object of the present invention is to provide such an improved method of and system for illuminating the surface of objects using a linear array of laser light emitting devices

configured together to produce a substantially planar beam of laser illumination which extends in substantially the same plane as the field of view of the linear array of electronic image detection cells of the system, along at least a portion of its optical path within its working distance,

Another object of the present invention is to provide such an image producing system, wherein the linear array of electronic image detection cells are realized using charge-coupled device (CCD) technology.

Another object of the present invention is to provide such an improved method of and system for producing digital images of objects using a visible laser diode array for producing a planar laser illumination beam for illuminating the surfaces of such objects, and also an electronic image detection array for detecting laser light reflected off the illuminated objects during illumination and imaging operations.

Another object of the present invention is to provide such an improved method of and system for illuminating the surfaces of object to be imaged, using an array of planar laser illumination arrays which employ VLDs that are smaller, and cheaper, run cooler, draw less power, have longer lifetimes, and require simpler optics (because their frequency bandwidths are very small compared to the entire spectrum of visible light).

Another object of the present invention is to provide such an improved method of and system for illuminating the surfaces of objects to be imaged, wherein the VLD concentrates all of its output power into a thin laser beam illumination plane which spatially coincides exactly with the field of view of the imaging optics of the system, so very little light energy is wasted.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein the working distance of the system can be easily extended by simply changing the beam focusing and imaging optics, and without increasing the output power of the visible laser diode (VLD) sources employed therein.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein each planar laser illumination beam is focused so that the minimum width thereof (e.g. 0.6 mm along its non-spreading direction) occurs at a point or plane which is the farthest object distance at which the system is designed to capture images.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein a fixed focal length imaging subsystem is employed, and the laser beam focusing technique of the present invention helps compensate for decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam for increasing distances away from the imaging subsystem.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein a variable focal length (i.e. zoom) imaging subsystem is employed, and the laser beam focusing technique of the present invention helps compensate for (i) decreases in the power density of the incident illumination beam due to the fact that the width of the planar laser illumination beam (i.e. beamwidth) along the direction of the beam's planar extent increases for increasing distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser illumination beam of the present invention.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein scanned objects need only be illuminated along a single plane which is coplanar with a planar section of the field of view of the image formation and detection module being used in the PLIIM system.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein low-power, light-weight, high-response, ultra-compact, high-efficiency solid-state illumination producing devices, such as visible laser diodes (VLDs), are used to selectively illuminate ultra-narrow sections of a target object during image formation and detection operations, in contrast with high-power, low-response, heavy-weight, bulky, low-efficiency lighting equipment (e.g. sodium vapor lights) required by prior art illumination and image detection systems.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein the planar laser illumination technique of the present invention enables high-speed modulation of the planar laser illumination beam, and use of simple (i.e. substantially monochromatic) lens designs for substantially monochromatic optical illumination and image formation and detection operations.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein special measures are undertaken to ensure that (i) a minimum safe distance is maintained between the VLDs in each PLIM and the user's eyes using a light shield, and (ii) the planar laser illumination beam is prevented from directly scattering into the FOV of the image formation and detection module within the system housing.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein the planar laser illumination beam and the field of view of the image formation and detection module do not overlap on any optical surface within the PLIIM system.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein the planar laser illumination beams are permitted to spatially overlap with the FOV of the imaging lens of the PLIIM only outside of the system housing, measured at a particular point beyond the light transmission window, through which the FOV is projected.

Another object of the present invention is to provide a planar laser illumination (PLIM) system for use in illuminating objects being imaged.

Another object of the present invention is to provide planar laser illumination and substantially-monochromatic imaging system, wherein the monochromatic imaging module is realized as an array of electronic image detection cells (e.g. CCD).

Another object of the present invention is to provide a planar laser illumination and substantially-monochromatic imaging system, wherein the planar laser illumination arrays (PLIAs) and the image formation and detection (IFD) module are mounted in strict optical alignment on an optical bench such that there is substantially no relative motion, caused by vibration or temperature changes, is permitted between the imaging lens within the IFD module and the VLD/cylindrical lens assemblies within the PLIAs.

Another object of the present invention is to provide a planar laser illumination and substantially-monochromatic imaging system, wherein the imaging module is realized as a photographic image recording module.

Another object of the present invention is to provide a planar laser illumination and substantially-monochromatic imaging system, wherein the imaging module is realized as an array of electronic image detection cells (e.g. CCD) having short integration time settings for high-speed image capture operations.

Another object of the present invention is to provide a planar laser illumination and substantially-monochromatic imaging system, wherein a pair of planar laser illumination arrays are mounted about an image formation and detection module having a field of view, so as to produce a substantially planar laser illumination beam which is coplanar with the field of view during object illumination and imaging operations.

Another object of the present invention is to provide a planar laser illumination and monochromatic imaging system, wherein an image formation and detection module projects a field of view through a first light transmission aperture formed in the system housing, and a pair of planar laser illumination arrays project a pair of planar laser illumination beams through second set of light transmission apertures which are optically isolated from the first light transmission aperture to prevent laser beam scattering within the housing of the system.

Another object of the present invention is to provide a planar laser illumination and substantially-monochromatic imaging system, the principle of Gaussian summation of light intensity distributions is employed to produce a planar laser illumination beam having a power density across the width the beam which is substantially the same for both far and near fields of the system.

Another object of the present invention is to provide method of and system for illuminating the surfaces of objects during image formation and detection operations.

Another object of the present invention is to provide method of and system for producing digital images of objects using planar laser illumination beams and electronic image detection arrays.

Another object of the present invention is to provide method of and system for producing a planar laser illumination beam to illuminate the surface of objects and electronically detecting light reflected off the illuminated objects during planar laser beam illumination operations.

Another object of the present invention is to provide hand-held laser illuminated image detection and processing device for use in reading bar code symbols and other character strings.

Another object of the present invention is to provide method of and system for producing images of objects by focusing a planar laser illumination beam within the field of view of an imaging lens so that the minimum width thereof along its non-spreading direction occurs at the farthest object distance of the imaging lens.

Another object of the present invention is to provide planar laser illumination modules for use in electronic imaging systems, and methods of designing and manufacturing the same.

Another object of the present invention is to provide planar laser illumination arrays for use in electronic imaging systems, and methods of designing and manufacturing the same.

Another object of the present invention is to provide a unitary object attribute (i.e. feature) acquisition and analysis system completely contained within in a single housing of compact lightweight construction (e.g. less than 40 pounds).

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, which is capable of (1) acquiring and analyzing in real-time the physical attributes of objects such as, for example, (i) the surface reflectively characteristics of objects, (ii) geometrical characteristics of objects, including shape measurement, (iii) the motion (i.e. trajectory) and velocity of objects, as well as (iv) bar code symbol, textual, and other information-bearing structures disposed thereon, and (2) generating information structures representative thereof for use in diverse applications including, for example, object identification, tracking, and/or transportation/routing operations.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein a multi-wavelength i.e. color-sensitive) Laser Doppler Imaging and Profiling (LDIP) subsystem is provided for acquiring and analyzing (in real-time) the physical attributes of objects such as, for example, (i) the surface reflectively characteristics of objects, (ii) geometrical characteristics of objects, including shape measurement, and (iii) the motion (i.e. trajectory) and velocity of objects.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein an image formation and detection (i.e. camera) subsystem is provided having (i) a planar laser illumination and monochromatic imaging (PLIIM) subsystem, (ii) intelligent auto-focus/auto-zoom imaging optics, and (iii) a high-speed electronic image detection array with height/velocity-driven photo-integration time control to ensure the capture of images having constant image resolution (i.e. constant dpi) independent of package height..

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein an advanced image-based bar code symbol decoder is provided for reading 1-D and 2-D bar code symbol labels on objects, and an advanced optical character recognition (OCR) processor is provided for reading textual information, such as alphanumeric character strings, representative within digital images that have been captured and lifted from the system .

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system for use in the high-speed parcel, postal and material handling industries.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, which is capable of being used to identify, track and route packages, as well as identify individuals for security and personnel control applications.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system which enables bar code symbol reading of linear and two-dimensional bar codes, OCR-compatible image lifting, dimensioning, singulation, object (e.g. package) position and velocity measurement, and label-to-parcel tracking from a single overhead-mounted housing measuring less than or equal to 20'' in width, 20'' in length, and 8'' in height.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system which employs a built-in source for producing a planar laser illumination beam that is coplanar with the field of view of the imaging optics used to form images on an electronic image detection array, thereby eliminating the need for large, complex, high-power power consuming sodium vapor lighting equipment used in conjunction with most industrial CCD cameras.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein the all-in-one (i.e. unitary) construction simplifies installation, connectivity, and reliability for customers as it utilizes a single input cable for supplying input (AC) power and a single output cable for outputting digital data to host systems.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein such systems can be configured to construct multi-sided tunnel-type imaging systems, used in airline baggage handling systems, as well as in postal and parcel identification, dimensioning and sortation systems.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, for use in (i) automatic checkout solutions installed within retail shopping environments (e.g. supermarkets), (ii) security and people analysis applications, (iii) object and/or material identification and inspection systems, as well as (iv) diverse portable, in-counter and fixed applications in virtual any industry.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system in the form of a high-speed package dimensioning and identification system, wherein the PLIIM subsystem projects a field of view through a first light transmission aperture formed in the system housing, and a pair of planar laser illumination beams through second and third light transmission apertures which are optically isolated from the first light transmission aperture to prevent laser beam scattering within the housing of the system, and the LDIP subsystem projects a pair of laser beams at different angles through a fourth light transmission aperture.

Another object of the present invention is to provide a fully automated unitary-type package identification and measuring system (i.e. contained within a single housing or enclosure), wherein a PLIIM-based scanning subsystem is used to read bar codes on packages passing below or near the system, while a package dimensioning subsystem is used to capture information about attributes (i.e. features) about the package prior to being identified.

Another object of the present invention is to provide such an automated package identification and measuring system, wherein Laser Detecting And Ranging (LADAR-based) scanning methods are used to capture two-dimensional range data maps of the space above a conveyor belt structure, and two-dimensional image contour tracing methods are used to extract package dimension data therefrom.

Another object of the present invention is to provide such a unitary system, wherein the package velocity is automatically computed using a pair of laser beams projected at different angular projections over the conveyor belt.

Another object of the present invention is to provide such system in which lasers beams having multiple wavelengths are used to sense packages having a wide range of reflectivity characteristics.

Another object of the present invention is to provide improved image-based hand-held scanners, body-wearable scanners, presentation-type scanners, and hold-under scanners which embody the PLIIM subsystem of the present invention.

Another object of the present invention is to provide a novel planar laser illumination and imaging system (PLIIM) which employs a planar laser illumination array (PLIA) that effectively reduces the speckle-noise pattern observed at the image detection array of the PLIIM system by destroying the spatial and/or temporal coherence of the laser illumination sources in the PLIA that are used to generate planar laser illumination beams (PLIBs) within the PLIIM system.

Another object of the present invention is to provide such PLIIM-based system, wherein the spatial coherence of the laser illumination sources is destroyed by creating multiple "virtual" illumination sources that illuminate the object at different points in space, over the photo-integration time period of the electronic image detection array used in the system.

Another object of the present invention is to provide such a PLIIM-based system, wherein the individual beam components within the composite planar laser illumination beam produced by the PLIA are (i) micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) at a rate of change which is greater than or equal to the inverse of the photo-integration time period of the detector elements.

Another object of the present invention is to provide such a PLIIM-based system, wherein under such conditions, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. On a time-average basis, the coherent addition of laser illumination from such moving virtual illumination sources, causes a change in the illumination field detected at each image detection element in the IFD module (i.e. digital camera subsystem). This destroys the spatial coherence of the laser illumination beam received at the detector elements and thereby reduces the speckle-noise pattern (i.e. level) produced thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle noise amplitude should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof.

Another object of the present invention is to provide such a PLIIM-based system, wherein the "temporal" coherence of the illumination sources is destroyed by creating multiple "virtual" illumination sources that illuminate the object at different moments in time, over the photo-integration time period of the electronic image detection array used in the system.

Another object of the present invention is to provide such a PLIIM-based system, wherein (i) the wavefront of each individual beam component within the composite planar laser illumination beam produced by the PLIA is either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta \phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change in such wavefront modulation is greater than or equal to the inverse of the photo-integration time period of the detector elements.

Another object of the present invention is to provide such a PLIIM-based system, wherein under such conditions, the target object is repeatedly illuminated with laser light apparently originating from different moments in time over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. .On a time-average basis, the coherent addition of laser illumination from such moving virtual illumination sources, causes a change in the illumination field detected at each image detection element in the IFD module (i.e. digital camera subsystem). This destroys the spatial coherence of the laser illumination beam received at the detector elements and thereby reduces the speckle-noise pattern (i.e. level) produced thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle noise amplitude should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof.

Another object of the present invention is to provide a unitary (PLIIM-based) package dimensioning and identification system, wherein the various information signals are generated by the LDIP subsystem, and provided to the Camera Control (Computer) Subsystem. and wherein the Camera Control Computer generates digital camera control signals which are provided to the image formation and detection (IFD subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either a image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations.

As will be described in greater detail in the Detailed Description of the Illustrative Embodiments set forth below, such objectives are achieved in novel methods of and systems for illuminating objects (e.g. bar coded packages, textual materials, graphical indicia, etc.) using planar laser illumination beams (PLIBs) having substantially-planar spatial distribution

characteristics that extend through the field of view (FOV) of image formation and detection modules (e.g. realized within a CCD-type digital electronic camera, or a 35 mm optical-film photographic camera) employed in such systems.

In each illustrative embodiment of the present invention, the substantially planar laser illumination beams are preferably produced from a planar laser illumination beam array (PLIA) comprising a plurality of planar laser illumination modules (PLIMs). Each PLIM comprises a visible laser diode (VLD), a focusing lens, and a cylindrical optical element arranged therewith. The individual planar laser illumination beam components produced from each PLIM are optically combined within the PLIA to produce a composite substantially planar laser illumination beam having substantially uniform power density characteristics over the entire spatial extend thereof and thus the working range of the system.

Preferably, each planar laser illumination beam component is focused so that the minimum beam width thereof occurs at a point or plane which is the farthest or maximum object distance at which the system is designed to acquire images. In the case of both fixed and variable focal length imaging systems, this inventive principle helps compensate for decreases in the power density of the incident planar laser illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem.

By virtue of the novel principles of the present invention, it is now possible to use both VLDs and high-speed CCD-type image detectors in conveyor, hand-held and hold-under type scanning applications alike, enjoying the advantages and benefits that each such technology has to offer, while avoiding the shortcomings and drawbacks hitherto associated therewith.

These and other objects of the present invention will become apparent hereinafter and in the Claims to Invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention. the following Detailed Description of the Illustrative Embodiment should be read in conjunction with the accompanying Drawings, wherein:

Fig. 1A is a schematic representation of a first generalized embodiment of the planar laser illumination and (electronic) imaging (PLIIM) system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear (i.e. 1-dimensional) type image formation and detection module (IFDM) having a fixed focal length imaging lens, a fixed focal distance and fixed field of view, such that the planar illumination array produces a stationary (i.e. non-scanned) plane of laser beam illumination which is disposed substantially coplanar with the field of view of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system on a moving bar code symbol or other graphical structure;

Fig. 1B1 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, wherein the field of view of the image formation and detection module is folded in the downwardly imaging direction by the field of

view folding mirror so that both the folded field of view and resulting stationary planar laser illumination beams produced by the planar illumination arrays are arranged in a substantially coplanar relationship during object illumination and image detection operations, and a planar laser illumination beam (PLIB) micro-oscillation mechanism is used to micro-oscillate each beam component within and along the planar extent of the composite planar laser illumination beam by a relatively small distance with respect to each detector element in the stationary linear image detection array of the PLIIM system, so as to repeatedly illuminate the target object with laser light apparently originating from a different point in space over the photo-integration period of the detector element, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1B2 is a schematic representation of the PLIIM system shown in Fig. 1A, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, each planar laser illumination array is shown comprising an array of planar laser illumination modules, and a planar laser illumination beam (PLIB) micro-oscillation mechanism is used to micro-oscillate each beam component within the composite planar laser illumination beam produced by the planar laser illumination array to destroy the spatial coherence of the laser illumination beam received at the detector element and thereby reduce the speckle-noise pattern produced thereat;

Fig. 1C is a schematic representation of a single planar laser illumination module (PLIM) used to construct each planar laser illumination array shown in Fig. 1B, wherein the planar laser illumination beam emanates substantially within a single plane along the direction of beam propagation towards an object to be optically illuminated;

Fig. 1D is a schematic diagram of the planar laser illumination module of Fig. 1C, shown comprising a visible laser diode (VLD), a light collimating lens, and a cylindrical-type lens element configured together to produce a beam of planar laser illumination;

Fig. 1E1 is a plan view of the VLD, collimating lens and cylindrical lens assembly employed in the planar laser illumination module of Fig. 1C, showing that the focused laser beam from the collimating lens is directed on the input side of the cylindrical lens, and the output beam produced therefrom is a planar laser illumination beam expanded (i.e. spread out) along the plane of propagation;

Fig. 1E2 is an elevated side view of the VLD, collimating lens and cylindrical lens assembly employed in the planar laser illumination module of Fig. 1C, showing that the laser beam is transmitted through the cylindrical lens without expansion in the direction normal to the plane of propagation, but is focused by the collimating lens at a point residing within a plane located at the farthest object distance supported by the PLIIM system;

Fig. 1F is a block schematic diagram of the PLIIM system shown in Fig. 1A, comprising a pair of planar laser illumination arrays (driven by a set of VLD driver circuits that can drive the VLDs in a high-frequency pulsed-mode of operation), a linear-type image formation and detection module, a stationary field of view folding mirror, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 1G1 is a schematic representation of an exemplary realization of the PLIIM system of Fig. 1A, shown comprising a linear image formation and detection module, a pair of planar laser illumination arrays, and a field of view (FOV) folding mirror for folding the fixed field of view of the linear image formation and detection module in a direction that is coplanar with the plane of laser illumination beams produced by the planar laser illumination arrays;

Fig. 1G2 is a plan view schematic representation of the PLIIM system, taken along line 1G2-1G2 in Fig. 1G1, showing the spatial extent of the fixed field of view of the linear image formation and detection module in the illustrative embodiment of the present invention;

Figs. 1G3A is an elevated end view schematic representation of the PLIIM system, taken along line 1G3-1G3 in Fig. 1G1, showing the fixed field of view of the linear image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, the planar laser illumination beam produced by each planar laser illumination module being directed in the imaging direction such that both the folded field of view and planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations, and a planar laser illumination beam (PLIB) micro-oscillation mechanism used to micro-oscillate each beam component within the composite planar laser illumination beam produced by the planar laser illumination array so as to destroy the spatial coherence of the laser illumination beam received at the detector element and thereby reduce the speckle-noise pattern produced thereat;

Fig. 1G3B is an elevated end view schematic representation of the PLIIM system as shown in Fig. 1G3A, wherein the planar laser illumination beam (PLIB) micro-oscillation mechanism is shown so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change in such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G4 is an elevated side view schematic representation of the PLIIM system, taken along line 1G4-1G4 in Fig. 1G1, showing the field of view of the image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed along the imaging direction such that both the folded field of view and stationary planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 1G5 is an elevated side view of the PLIIM system of Fig. 1G1, showing the spatial limits of the fixed field of view (FOV) of the image formation and detection module when set to

image the tallest packages moving on a conveyor belt structure, as well as the spatial limits of the fixed FOV of the image formation and detection module when set to image objects having height values close to the surface height of the conveyor belt structure;

Fig. 1G6 is a perspective view of a first type of light shield which can be used in the PLIIM system of Fig. 1G1, to visually block portions of planar laser illumination beams that extend beyond the scanning field of the system, but which could pose a health risk to humans if viewed thereby during system operation;

Fig. 1G7 is a perspective view of a second type of light shield which can be used in the PLIIM system of Fig. 1G1, to visually block portions of planar laser illumination beams that extend beyond the scanning field of the system, but which could pose a health risk to humans if viewed thereby during system operation;

Fig. 1G8 is a perspective view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, showing an array of visible laser diodes (VLDs), each mounted within a VLD mounting block wherein a focusing lens is mounted and on the end of which there is a v-shaped notch or recess, within which a cylindrical lens element is mounted, and wherein each such VLD mounting block is mounted on an L-bracket for mounting within the housing of the PLIIM system;

Fig. 1G9 is an elevated end view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, taken along line 1G9-1G9 thereof;

Fig. 1G10 is an elevated side view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, taken along line 1G10-1G10 thereof, showing a visible laser diode (VLD) and a focusing lens mounted within a VLD mounting block, and a cylindrical lens element mounted at the end of the VLD mounting block, so that the central axis of the cylindrical lens element is substantially perpendicular to the optical axis of the focusing lens;

Fig. 1G11 is an elevated side view of one of the VLD mounting blocks employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is orthogonal to the central axis of the cylindrical lens element mounted to the end portion of the VLD mounting block;

Fig. 1G12 is an elevated plan view of one of VLD mounting blocks employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is parallel to the central axis of the cylindrical lens element mounted to the VLD mounting block;

Fig. 1G13 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by a refractive-type cylindrical lens array that is micro-oscillated by a pair of ultrasonic transducers arranged in a push-pull configuration so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image

detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G13A is a geometrical model of a subsection of the optical assembly shown in Fig. 1G13, illustrating the first order parameters involved in the PLIB micro-oscillation process that is used to destroy the spatial coherence of the laser illumination sources employed in PLIA and thereby mitigate speckle-type noise patterns observed at each of the elements in the image detection array employed with the PLIA in the PLIIM system of the present invention;

Fig. 1G13B1 is a pictorial representation of a string of numbers imaged by the PLIIM system of the present invention without the use of the speckle-noise reduction techniques of the present invention;

Fig. 1G13B2 is a pictorial representation of the same string of numbers (shown in Fig. 1G13B1) imaged by the PLIIM system of the present invention using the speckle-noise reduction techniques of the present invention, and showing a significant mitigation in speckle-noise patterns in digital images captured by the electronic image detection array employed in the PLIIM system;

Fig. 1G14 is a perspective view of the refractive-type cylindrical lens array employed in the optical assembly shown in Fig. 1G13;

Fig. 1G15 is a perspective view of the array support frame employed in the optical assembly shown in Fig. 1G13;

Fig. 1G16 is a schematic representation of the refractive-type cylindrical lens array employed in Fig. 1G13. shown configured between a pair of ultrasonic transducers (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation;

Fig. 1G17 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by (a holographically-fabricated) diffractive-type cylindrical lens array that is micro-oscillated by a pair of ultrasonic transducers arranged in a push-pull configuration so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G18 is a perspective view of the refractive-type cylindrical lens array employed in the optical assembly shown in Fig. 1G17;

Fig. 1G19 is a perspective view of the array support frame employed in the optical assembly shown in Fig. 1G17;

Fig. 1G20 is a schematic representation of the refractive-type cylindrical lens array employed in Fig. 1G17, shown configured between a pair of ultrasonic transducers (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation;

Fig. 1G21 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by a stationary reflective element fixedly mounted in front of a refractive-type cylindrical lens array, and a pair of micro-oscillating reflective elements that are micro-oscillated about a common pivot point by a pair of ultrasonic transducers arranged in a push-pull configuration, so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam components by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G22 is a enlarged perspective view of the pair of micro-oscillating reflective elements employed in the optical assembly shown in Fig. 1G21;

Fig. 1G23 is a schematic representation, taken along an elevated side view of the optical assembly shown in Fig. 1G21, showing the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated;

Fig. 1G24 is a schematic representation of one micro-oscillating reflective element in the pair employed in Fig. 1G21, shown configured between a pair of ultrasonic transducers operated in a push-pull mode of operation, so as to undergo micro-oscillation;

Fig. 1G25 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by an acousto-optical (i.e. Bragg Cell) beam deflection device through which each laser beam within the PLIM is transmitted and deflected in response to acoustical signals propagating through the electro-acoustical device so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element in the linear image

detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G26 is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1G25, showing the optical path which each laser beam within the PLIM travels on its way towards a target object to be illuminated;

Fig. 1G27 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by (i) a piezo-electrically driven deformable mirror (DM) structure arranged in front of a stationary cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), and (ii) a stationary beam folding mirror, wherein the surface of the DM structure is periodically deformed at frequencies in the 100kHz range and at few microns amplitude so that the reflective surface thereof exhibits moving ripples aligned along the direction that is perpendicular to planar extent of the planar laser illumination beam (i.e. along laser beam spread) so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating from different points in space over the photo-integration time period of each detector element, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G28 is a enlarged perspective view of the stationary beam folding mirror structure employed in the optical assembly shown in Fig. 1G27;

Fig. 1G29 is a schematic representation, taken along an elevated side view of the optical assembly shown in Fig. 1G21, showing the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated while undergoing phase modulation by the piezo-electrically driven deformable mirror structure;

Fig. 1G30 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and an electrically-active PLIB modulation mechanism realized by a high-speed laser beam modulation structure (e.g. electro-optical gating device) arranged in front of the cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), wherein (i) the wavefront of each individual beam component within the composite planar laser illumination beam is either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta \phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of

change in such wavefront modulation is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating at different moments in time over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the temporal coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G31 is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1G30, showing the optical path which each optically-gated laser beam within the PLIM travels on its way towards the target object to be illuminated;

Fig. 1G32 is a perspective view of an optical assembly comprising the PLIA of Fig. 1G8 and an electrically-passive PLIB modulation mechanism realized by a high-frequency optically-resonant cavity (e.g. electrically-passive ethalon device) arranged in front of the cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), wherein (i) the wavefront of each individual beam component within the composite planar laser illumination beam is either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta \phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change in such wavefront modulation is greater than or equal to the inverse of the photo-integration time period of the detector elements, thereby repeatedly illuminating the target object with laser light apparently originating at different moments in time over the photo-integration time period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the temporal coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat;

Fig. 1G33 is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1G33, showing the optical path which each optically-gated laser beam within the PLIM travels on its way towards a target object to be illuminated;

Fig. 1H1 is an elevated side view of the collimating lens element installed within each VLD mounting block employed in the PLIIM system of Fig. 1G1;

Fig. 1H2 is an axial view of the collimating lens element installed within each VLD mounting block employed in the PLIIM system of Fig. 1G1;

Fig. 1I1 is an elevated plan view of one of planar laser illumination modules (PLIMs) employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is parallel to the central axis of the cylindrical lens element mounted in the VLD mounting block thereof, showing that the cylindrical lens element expands (i.e. spreads out) the laser beam along the direction of beam propagation so that a substantially planar laser illumination beam is produced, which is characterized by a plane of propagation that is coplanar with the direction of beam propagation;

Fig. 1I2 is an elevated plan view of one of the PLIMs employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is perpendicular to the central axis of the cylindrical lens element mounted within the axial bore of the VLD mounting block thereof, showing that the focusing lens planar focuses the laser beam to its minimum beam width at a point which is the farthest distance at which the system is designed to capture images, while the cylindrical lens element does not expand or spread out the laser beam in the direction normal to the plane of propagation of the planar laser illumination beam;

Fig. 1J1 is a geometrical optics model for the imaging subsystem employed in the linear-type image formation and detection module in the PLIIM system of the first generalized embodiment shown in Fig. 1A;

Fig. 1J2 is a geometrical optics model for the imaging subsystem and linear image detection array employed in linear-type image detection array employed in the image formation and detection module in the PLIIM system of the first generalized embodiment shown in Fig. 1A;

Fig. 1J3 is a graph, based on thin lens analysis, showing that the image distance at which light is focused through a thin lens is a function of the object distance at which the light originates;

Fig. 1J4 is a schematic representation of an imaging subsystem having a variable focal distance lens assembly, wherein a group of lens can be controllably moved along the optical axis of the subsystem, and having the effect of changing the image distance to compensate for a change in object distance, allowing the image detector to remain in place;

Fig. 1J5 is schematic representation of a variable focal length (zoom) imaging subsystem which is capable of changing its focal length over a given range: so that a longer focal length produces a smaller field of view at a given object distance:

Fig. 1J6 is a schematic representation of an illustrative embodiment of the image formation and detection (IFD) module employed in the PLIIM systems of the present invention, wherein various optical parameters used to model the system are defined and graphically indicated wherever possible;

Fig. 1K1 is a schematic representation illustrating how the field of view of a PLIIM system can be fixed to substantially match the scan field width thereof (measured at the top of the scan field) at a substantial distance above a conveyor belt;

Fig. 1K2 is a schematic representation illustrating how the field of view of a PLIIM system can be fixed to substantially match the scan field width of a low profile scanning field slightly above the conveyor belt surface, by fixed the focal length of the imaging subsystem during the optical design stage;

Fig. 1L is a schematic representation illustrating how an arrangement of FOV beam folding mirrors can be used to produce an expanded FOV that matches the geometrical characteristics of the scanning application at hand, when the FOV emerges from the system housing;

Fig. 1L2 is a schematic representation illustrating how the fixed field of view of an imaging subsystem can be expanded across a working space (e.g. conveyor belt structure) by rotating the FOV during object illumination and imaging operations;

Fig. 1M1 shows a data plot of pixel power density E_{pix} vs. object distance r calculated using the arbitrary but reasonable values $E_0 = 1$ W/m^2, $f = 80$ mm and $F = 4.5$, demonstrating that, in a counter-intuitive manner, the power density at the pixel (and therefore the power incident on the pixel, since its area remains constant) actually increases as the object distance increases;

Fig. 1M2 is data plot of laser beam power density vs. position along the planar laser beam width showing that the total output power in the planar laser illumination beam of the present invention is distributed along the width of the beam in a roughly Gaussian distribution;

Fig. 1M3 shows a plot of beam width length L vs. object distance r calculated using a beam fan/spread angle $\theta = 50°$, demonstrating that the planar laser beam width increases as a function of increasing object distance;

Fig. 1M4 is a typical data plot of planar laser beam height h vs. image distance r for a planar laser illumination beam of the present invention focused at the farthest working distance in accordance with the principles of the present invention, demonstrating that the height dimension of the planar laser beam decreases as a function of increasing object distance;

Fig. 1N is a data plot of planar laser beam power density E_0 at the center of its beam width, plotted as a function of object distance, demonstrating that use of the laser beam focusing technique of the present invention, wherein the height of the planar laser illumination beam is decreased as the object distance increases, compensates for the increase in beam width in the planar laser illumination beam, which occurs for an increase in object distance, thereby yielding a laser beam power density on the target object which increases as a function of increasing object distance over a substantial portion of the object distance range of the PLIIM system;

Fig. 1O is a data plot of pixel power density E_0 vs. object distance, obtained when using a planar laser illumination beam whose beam height decreases with increasing object distance, and also a data plot of the "reference" pixel power density plot E_{pix} vs. object distance obtained when using a planar laser illumination beam whose beam height is substantially constant (e.g. 1 mm) over the entire portion of the object distance range of the PLIIM system;

Fig. 1P1 is a schematic representation of the composite power density characteristics associated with the planar laser illumination array in the PLIIM system of Fig. 1G1, taken at the "near field region" of the system, and resulting from the additive contributions of the individual visible laser diodes in the planar laser illumination arrays;

Fig. 1P2 is a schematic representation of the composite power density characteristics associated with the planar laser illumination array in the PLIIM system of Fig. 1G1, taken at the "far field region" of the system, and resulting from the additive contributions of the individual visible laser diodes in the planar laser illumination arrays;

Fig. 1Q1 is a schematic representation of second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, shown comprising a linear image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the field of view thereof is oriented in a direction that is coplanar with the plane of the stationary planar laser illumination beams produced by the planar laser illumination arrays, without using any laser beam or field of view folding mirrors;

Fig. 1Q2 is a block schematic diagram of the PLIIM system shown in Fig. 1Q1, comprising a linear image formation and detection module, a pair of planar laser illumination arrays, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 1R1 is a schematic representation of third illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, shown comprising a linear image formation and detection module having a field of view, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second planar laser illumination beams such that the planes of the first and second stationary planar laser illumination beams are in a direction that is coplanar with the field of view of the image formation and detection module;

Fig. 1R2 is a block schematic diagram of the PLIIM system shown in Fig. 1P1, comprising a linear image formation and detection module, a stationary field of view folding mirror, a pair of planar illumination arrays, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 1S1 is a schematic representation of fourth illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, shown comprising a linear image formation and detection module having a field of view (FOV), a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser illumination beam folding mirrors for folding the optical paths of the first and second stationary planar laser illumination beams so that planes of first and second stationary planar laser illumination beams are in a direction that is coplanar with the field of view of the image formation and detection module;

Fig. 1S2 is a block schematic diagram of the PLIIM system shown in Fig. 1S1, comprising a linear-type image formation and detection module, a stationary field of view folding mirror, a pair of planar laser illumination arrays, a pair of stationary planar laser beam folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 1T is a schematic representation of an under (or over) the-conveyor belt package identification system embodying the PLIIM system of Fig. 1A;

Fig. 1U is a schematic representation of a hand-supportable bar code symbol reading system embodying the PLIIM system of Fig. 1A;

Fig. 1V1 is a is a schematic representation of second generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear type image formation and detection module (IFDM) having a field of view, such that the planar laser illumination arrays produce a plane of laser beam illumination (i.e. light) which is disposed substantially coplanar with the field of view of the image formation and detection module, and that the planar laser illumination beam and the field of view of the image formation and detection module move synchronously while

maintaining their coplanar relationship with each other as the planar laser illumination beam is automatically scanned over a 2-D region of space during object illumination and image detection operations;

Fig. 1V2 is a schematic representation of first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1V1, shown comprising an image formation and detection module having a field of view (FOV), a field of view (FOV) folding/sweeping mirror for folding the field of view of the image formation and detection module, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors, jointly or synchronously movable with the FOV folding/sweeping mirror, and arranged so as to fold and sweep the optical paths of the first and second planar laser illumination beams, so that the folded field of view of the image formation and detection module is synchronously moved with the planar laser illumination beams in a direction that is coplanar therewith as the planar laser illumination beams are scanned over a 2-D region of space under the control of the system controller;

Fig. 1V3 is a block schematic diagram of the PLIIM system shown in Fig. 1V1, comprising a pair of planar illumination arrays, a pair of planar laser beam folding/sweeping mirrors, a linear-type image formation and detection module, a field of view folding/sweeping mirror, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 1V4 is a schematic representation of an over-the-conveyor belt package identification system embodying the PLIIM system of Fig. 1V1;

Fig. 1V5 is a schematic representation of a presentation-type bar code symbol reading system embodying the PLIIM system of Fig. 1V1;

Fig. 2A is a schematic representation of a third generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear (i.e. 1-dimensional) type image formation and detection module (IFDM) having a fixed focal length imaging lens, a variable focal distance and a fixed field of view (FOV), so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module during object illumination and image detection operations carried out on bar code symbol structures and other graphical indicia which may embody information within its structure;

Fig. 2B1 is a schematic representation of a first illustrative embodiment of the PLIIM system shown in Fig. 2A, comprising an image formation and detection module having a field of view (FOV), and a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams in an imaging direction that is coplanar with the field of view of the image formation and detection module;

Fig. 2B2 is a schematic representation of the PLIIM system of the present invention shown in Fig. 2B1, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 2C1 is a block schematic diagram of the PLIIM system shown in Fig. 2B1, comprising a pair of planar illumination arrays, a linear-type image formation and detection module, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 2C2 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 2B1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system;

Fig. 2D1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 2A, shown comprising a linear image formation and detection module, a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the folded field of view is oriented in an imaging direction that is coplanar with the stationary planes of laser illumination produced by the planar laser illumination arrays;

Fig. 2D2 is a block schematic diagram of the PLIIM system shown in Fig. 2D1, comprising a pair of planar laser illumination arrays (PLIAs), a linear-type image formation and detection module, a stationary field of view of folding mirror, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 2D3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLLIM system shown in Fig. 2D1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system;

Fig. 2E1 is a schematic representation of the third illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, shown comprising an image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a pair of stationary planar laser beam folding mirrors for folding the stationary (i.e. non-swept) planes of the planar laser illumination beams produced by the pair of planar laser illumination arrays, in an imaging direction that is coplanar with the stationary plane of the field of view of the image formation and detection module during system operation;

Fig. 2E2 is a block schematic diagram of the PLIIM system shown in Fig. 2B1, comprising a pair of planar laser illumination arrays, a linear image formation and detection module, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 2E3 is a schematic representation of the linear image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 2B1, wherein an imaging subsystem having fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system;

Fig. 2F1 is a schematic representation of the fourth illustrative embodiment of the PLIIM system of the present invention shown in Fig. 2A, shown comprising a linear image formation and detection module having a field of view (FOV), a stationary field of view (FOV) folding mirror, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second stationary planar laser illumination beams so that these planar laser illumination beams are oriented in an imaging direction that is coplanar with the folded field of view of the linear image formation and detection module;

Fig. 2F2 is a block schematic diagram of the PLIIM system shown in Fig. 2F1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 2F3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 2F1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system;

Fig. 2G is a schematic representation of an over-the-conveyor belt package identification system embodying the PLIIM system of Fig. 2A;

Fig. 2H is a schematic representation of a hand-supportable bar code symbol reading system embodying the PLIIM system of Fig. 2A;

Fig. 2I1 is a schematic representation of the fourth generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection module (IFDM) having a fixed focal length imaging lens, a variable focal distance and fixed field of view (FOV), so that the planar illumination arrays produces a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module and synchronously moved therewith while the planar laser illumination beams are automatically scanned over a 2-D region of space during object illumination and imaging operations;

Fig. 2I2 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 2I1, shown comprising an image formation and detection module having a field of view (FOV), a field of view (FOV) folding/sweeping mirror, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors, jointly movable with the FOV folding/sweeping mirror, and arranged so that the field of view of the image formation and detection module is coplanar with the folded planes of first and second planar laser illumination beams, and the coplanar FOV and planar laser illumination beams are synchronously moved together while the planar laser illumination beams and FOV are scanned over a 2-D region of space containing a stationary or moving bar code symbol or other graphical structure (e.g. text) embodying information;

Fig. 2I3 is a block schematic diagram of the PLIIM system shown in Figs. 2I1 and 2I2, comprising a pair of planar illumination arrays, a linear image formation and detection module, a field of view (FOV) folding/sweeping mirror, a pair of planar laser illumination beam folding/sweeping mirrors jointly movable therewith, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 2I4 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Figs. 2I1 and 2I2, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system;

Fig. 2I5 is a schematic representation of a hand-supportable bar code symbol reader embodying the PLIIM system of Fig. 2I1;

Fig. 2I6 is a schematic representation of a presentation-type bar code symbol reader embodying the PLIIM system of Fig. 2I1;

Fig. 3A is a schematic representation of a fifth generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection module (IFDM) having a variable focal length imaging lens, a variable focal distance and a variable field of view, so that the planar laser illumination arrays produce a stationary plane of laser beam illumination (i.e. light) which is disposed substantially coplanar with the field view of the image formation and detection module during object illumination and image detection operations carried out on bar code symbol and other graphical indicia by the PLIIM system of the present invention;

Fig. 3B1 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 3A, shown comprising an image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the stationary field of view thereof is oriented in an imaging direction that is coplanar with the stationary plane of laser illumination produced by the planar laser illumination arrays, without using any laser beam or field of view folding mirrors.

Fig. 3B2 is a schematic representation of the first illustrative embodiment of the PLIIM system shown in Fig. 3B1, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 3C1 is a block schematic diagram of the PLIIM shown in Fig. 3B1, comprising a pair of planar laser illumination arrays, a linear image formation and detection module, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 3C2 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 3B1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system;

Fig. 3D is a schematic representation of an illustrative implementation of the imaging subsystem contained in the image formation and detection module employed in the PLIIM system of Fig. 3B1, shown comprising a stationary lens system mounted before the stationary linear image detection array, a first movable lens system for large stepped movement relative to the stationary lens system during image zooming operations, and a second movable lens system for small stepped movements relative to the first movable lens system and the stationary lens system during image focusing operations;

Fig. 3E1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection module, a pair of planar laser illumination arrays, and a stationary field of view (FOV) folding mirror arranged in relation to the image formation and detection module such that the stationary field of view thereof is oriented in an imaging direction that is coplanar with the stationary plane of laser illumination produced by the planar laser illumination arrays, without using any planar laser illumination beam folding mirrors;

Fig. 3E2 is a block schematic diagram of the PLIIM system shown in Fig. 3E1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 3E3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 3E1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system;

Fig. 3E4 is a schematic representation of the PLIIM system of Fig. 3E1, shown comprising a linear-type image formation and detection module, a pair of planar laser illumination arrays, and a field of view (FOV) folding mirror for folding the field of view of the image formation and detection module in a direction that is coplanar with the plane of laser illumination produced by the planar illumination arrays;

Fig. 3E5 is a plan view schematic representation of the PLIIM system, taken along line 3E5-3E5 in Fig. 3E4, showing the spatial extent of the field of view of the image formation and detection module in the illustrative embodiment of the present invention;

Fig. 3E6 is an elevated end view schematic representation of the PLIIM system, taken along line 3E6-3E6 in Fig. 3E4, showing the field of view of the linear image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed in the imaging direction such that both the folded field of view and planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and imaging operations;

Fig. 3E7 is an elevated side view schematic representation of the PLIIM system, taken along line 3E7-3E7 in Fig. 3E4, showing the field of view of the linear image formation and detection module being folded in the downwardly imaging direction by the field of view folding

mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed along the imaging direction such that both the folded field of view and stationary planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 3E8 is an elevated side view of the PLIIM system of Fig. 3E4, showing the spatial limits of the variable field of view (FOV) of the linear image formation and detection module when controllably adjusted to image the tallest packages moving on a conveyor belt structure, as well as the spatial limits of the variable FOV of the linear image formation and detection module when controllably adjusted to image objects having height values close to the surface height of the conveyor belt structure;

Fig. 3F1 is a schematic representation of the third illustrative embodiment of the PLIIM system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a pair of stationary planar laser illumination beam folding mirrors arranged relative to the planar laser illumination arrays so as to fold the stationary planar laser illumination beams produced by the pair of planar illumination arrays in an imaging direction that is coplanar with stationary field of view of the image formation and detection module during illumination and imaging operations;

Fig. 3F2 is a block schematic diagram of the PLIIM system shown in Fig. 3FF1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 3F3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 3F1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 3G1 is a schematic representation of the fourth illustrative embodiment of the PLIIM system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second planar laser illumination beams such that stationary planes of first and second planar laser illumination beams are in an imaging direction which is coplanar with the field of view of the image formation and detection module during illumination and imaging operations;

Fig. 3G2 is a block schematic diagram of the PLIIM system shown in Fig. 3G1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of stationary planar laser illumination beam

folding mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 3G3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 3G1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 3H is a schematic representation of an over-the-conveyor and side-of conveyor belt package identification systems embodying the PLIIM system of Fig. 3A;

Fig. 3I is a schematic representation of a hand-supportable bar code symbol reading device embodying the PLIIM system of Fig. 3A;

Fig. 3J1 is a schematic representation of the sixth generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection module (IFDM) having a variable focal length imaging lens, a variable focal distance and a variable field of view, so that the planar illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module and synchronously moved therewith as the planar laser illumination beams are scanned across a 2-D region of space during object illumination and image detection operations;

Fig. 3J2 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 3J1, shown comprising an image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, a field of view folding/sweeping mirror for folding and sweeping the field of view of the image formation and detection module, and a pair of planar laser beam folding/sweeping mirrors jointly movable with the FOV folding/sweeping mirror and arranged so as to fold the optical paths of the first and second planar laser illumination beams so that the field of view of the image formation and detection module is in an imaging direction that is coplanar with the planes of first and second planar laser illumination beams during illumination and imaging operations;

Fig. 3J3 is a block schematic diagram of the PLIIM system shown in Fig. 3J1 and 3J2, comprising a pair of planar illumination arrays. a linear image formation and detection module, a field of view folding/sweeping mirror, a pair of planar laser illumination beam folding/sweeping mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 3J4 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM system shown in Figs. 3J1 and J2, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 3J5 is a schematic representation of a hand-held bar code symbol reading system embodying the PLIIM subsystem of Fig. 3J1;

Fig. 3J6 is a schematic representation of a presentation-type bar code symbol reading system embodying the PLIIM subsystem of Fig. 3J1;

Fig. 4A is a schematic representation of a seventh generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area (i.e. 2-dimensional) type image formation and detection module (IFDM) having a fixed focal length camera lens, a fixed focal distance and fixed field of view projected through a 3-D scanning region, so that the planar illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module while the planar laser illumination beam is automatically scanned across the 3-D scanning region during object illumination and imaging operations carried out on a bar code symbol or other graphical indicia by the PLIIM system;

Fig. 4B1 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 4A, shown comprising an area image formation and detection module having a field of view (FOV) projected through a 3-D scanning region, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 4B2 is a schematic representation of PLIIM system shown in Fig. 4B1, wherein the linear image formation and detection module is shown comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 4B3 is a block schematic diagram of the PLIIM system shown in Fig. 4B1, comprising a pair of planar illumination arrays, an area-type image formation and detection module, a pair of planar laser illumination beam sweeping mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 4C1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 4A, comprising a area image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, a stationary field of view folding mirror for folding and projecting the field of view through a 3-D scanning region, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 4C2 is a block schematic diagram of the PLIIM system shown in Fig. 4C1, comprising a pair of planar illumination arrays, an area-type image formation and detection

module, a movable field of view folding mirror, a pair of planar laser illumination beam sweeping mirrors jointly or otherwise synchronously movable therewith, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 4D is a schematic representation of presentation-type holder-under bar code symbol reading system embodying the PLIIM subsystem of Fig. 4A;

Fig. 4E is a schematic representation of hand-supportable-type bar code symbol reading system embodying the PLIIM subsystem of Fig. 4A;

Fig. 5A is a schematic representation of an eighth generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area (i.e. 2-dimensional) type image formation and detection module (IFDM) having a fixed focal length imaging lens, a variable focal distance and a fixed field of view (FOV) projected through a 3-D scanning region, so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module as the planar laser illumination beams are automatically scanned through the 3-D scanning region during object illumination and image detection operations carried out on a bar code symbol or other graphical indicia by the PLIIM system;

Fig. 5B1 is a schematic representation of the first illustrative embodiment of the PLIIM system shown in Fig. 5A, shown comprising an image formation and detection module having a field of view (FOV) projected through a 3-D scanning region, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 5B2 is a schematic representation of the first illustrative embodiment of the PLIIM system shown in Fig. 5B1, wherein the linear image formation and detection module is shown comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 5B3 is a block schematic diagram of the PLIIM system shown in Fig. 5B1, comprising a short focal length imaging lens, a low-resolution image detection array and associated image frame grabber, a pair of planar illumination arrays, a high-resolution area-type image formation and detection module, a pair of planar laser beam folding/sweeping mirrors, an associated image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 5B4 is a schematic representation of the area-type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 5B1, wherein an imaging subsystem having a fixed length imaging lens, a variable focal distance and fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to

focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 5C1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 5A, shown comprising an image formation and detection module, a stationary FOV folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 5C2 is a schematic representation of the second illustrative embodiment of the PLIIM system shown in Fig. 6A, wherein the linear image formation and detection module is shown comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 5C3 is a block schematic diagram of the PLIIM system shown in Fig. 5C1, comprising a pair of planar illumination arrays, an area-type image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of planar laser illumination beam folding and sweeping mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 5C4 is a schematic representation of the area-type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 5C1, wherein an imaging subsystem having a fixed length imaging lens, a variable focal distance and fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 5D is a schematic representation of a presentation-type hold-under bar code symbol reading system embodying the PLIIM subsystem of Fig. 5A;

Fig. 6A is a schematic representation of a ninth generalized embodiment of the PLIIM system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area type image formation and detection module (IFDM) having a variable focal length imaging lens, a variable focal distance and variable field of view projected through a 3-D scanning region, so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module as the planar laser illumination beams are automatically scanned through the 3-D scanning region during object illumination and image detection operations carried out on a bar code symbol or other graphical indicia by the PLIIM system;

Fig. 6B1 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 6A, shown comprising an image formation and detection module, a pair of planar laser illumination arrays for producing first and second planar

laser illumination beams, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6B2 is a schematic representation of a first illustrative embodiment of the PLIIM system shown in Fig. 6B1, wherein the area image formation and detection module is shown comprising an area array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 6B3 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 6B1, shown comprising a pair of planar illumination arrays, an area-type image formation and detection module, a pair of planar laser beam folding/sweeping mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 6B4 is a schematic representation of the area-type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 6B1, wherein an imaging subsystem having a variable length imaging lens, a variable focal distance and variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 6C1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 6A, shown comprising an image formation and detection module, a stationary FOV folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6C2 is a schematic representation of a second illustrative embodiment of the PLIIM system shown in Fig. 6C1, wherein the area image formation and detection module is shown comprising an area array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 6C3 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 6C1, shown comprising a pair of planar illumination arrays, an area-type image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of planar laser illumination beam folding and sweeping

mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 6C4 is a schematic representation of the area-type image formation and detection module (IFDM) employed in the PLIIM system shown in Fig. 5C1, wherein an imaging subsystem having a variable length imaging lens, a variable focal distance and variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the system controller of the PLIIM system during illumination and imaging operations;

Fig. 6D is a schematic representation of a presentation type hold-under bar code symbol reading system embodying the PLIIM system of Fig. 6A;

Fig. 6D1 is a schematic representation of the PLIIM system of Fig. 6A, shown comprising an image formation and detection module, a stationary field of view (FOV) folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D2 is a plan view schematic representation of the PLIIM system, taken along line 6D2-6D2 in Fig. 6D1, showing the spatial extent of the field of view of the image formation and detection module in the illustrative embodiment of the present invention;

Fig. 6D3 is an elevated end view schematic representation of the PLIIM system, taken along line 6D3-6D3 in Fig. 6D1, showing the FOV of the area image formation and detection module being folded by the stationary FOV folding mirror and projected downwardly through a 3-D scanning region, and the planar laser illumination beams produced from the planar laser illumination arrays being folded and swept so that the optical paths of these planar laser illumination beams are oriented in a direction that is coplanar with a section of the FOV of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D4 is an elevated side view schematic representation of the PLIIM system, taken along line 6D4-6D4 in Fig. 6D1, showing the FOV of the area image formation and detection module being folded and projected downwardly through the 3-D scanning region, while the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D5 is an elevated side view of the PLIIM system of Fig. 6D1, showing the spatial limits of the variable field of view (FOV) provided by the area image formation and detection module when imaging the tallest package moving on a conveyor belt structure must be imaged. as well as the spatial limits of the FOV of the image formation and detection module when imaging objects having height values close to the surface height of the conveyor belt structure;

Fig. 6E1 is a schematic representation of a tenth generalized embodiment of the PLIIM system of the present invention, wherein a 3-D field of view and a pair of planar laser illumination beams are controllably steered about a 3-D scanning region;

Fig. 6E2 is a schematic representation of the PLIIM system shown in Fig. 6E1, shown comprising an area-type image formation and detection module, a pair of planar laser illumination arrays, a pair of x and y axis field of view (FOV) folding mirrors arranged in relation to the image formation and detection module, and a pair of x and y axis planar laser illumination beam sweeping mirrors arranged in relation to the pair of planar laser beam illumination mirrors, such that the planes of laser illumination are coplanar with a planar section of the 3-D field of view of the image formation and detection module as the planar laser illumination beams are automatically scanned across a 3-D region of space during object illumination and image detection operations;

Fig. 6E3 is a schematic representation of the PLIIM system shown in Fig. 6E1, shown comprising an image formation and detection module, a pair of planar laser illumination arrays, a pair of x and y axis FOV folding mirrors arranged in relation to the image formation and detection module, and a pair of x and y axis planar laser illumination beam sweeping mirrors arranged in relation to the pair of planar laser beam illumination mirrors, an image frame grabber, an image data buffer, a decode image processor, and a system controller;

Fig. 6E4 is a schematic representation showing a portion of the PLIIM system in Fig. 6E1, wherein the 3-D field of view of the image formation and detection module is steered over the 3-D scanning region of the system using the x and y axis FOV folding mirrors, working in cooperation with the x and y axis planar laser illumination beam folding mirrors which steer the pair of planar laser illumination beams in accordance with the principles of the present invention;

Fig. 7A is a schematic representation of a first illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention, wherein (i) a pair of planar laser illumination arrays are used to generate a composite planar laser illumination beam for illuminating a target object, (ii) a holographic-type cylindrical lens is used to collimate the rays of the planar laser illumination beam down onto the a conveyor belt surface, and (iii) a motor-driven holographic imaging disc, supporting a plurality of transmission-type volume holographic optical elements (HOE) having different focal lengths, is disposed before a linear (1-D) CCD image detection array, and functions as a variable-type imaging subsystem capable of detecting images of objects over a large range of object (i.e. working) distances while the planar laser illumination beam illuminates the object;

Fig. 7B is an elevated side view of the hybrid holographic/CCD-based PLIIM system of Fig. 7A, showing the coplanar relationship between the planar laser illumination beam(s) produced by the planar laser illumination arrays of the PLIIM system, and the variable field of view (FOV) produced by the variable holographic-based focal length imaging subsystem of the PLIIM system;

Fig. 8A is a schematic representation of a second illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention, wherein (i) a pair of planar laser illumination arrays are used to generate a composite planar laser illumination beam for illuminating a target object, (ii) a holographic-type cylindrical lens is used to collimate the rays of the planar laser illumination beam down onto the a conveyor belt surface, and (iii) a motor-driven holographic imaging disc, supporting a plurality of transmission-type volume holographic optical elements (HOE) having different focal lengths, is disposed before an area (2-D) CCD

image detection array, and functions as a variable-type imaging subsystem capable of detecting images of objects over a large range of object (i.e. working) distances while the planar laser illumination beam illuminates the object;

Fig. 8B is an elevated side view of the hybrid holographic/CCD-based PLIIM system of Fig. 8A, showing the coplanar relationship between the planar laser illumination beam(s) produced by the planar laser illumination arrays of the PLIIM system, and the variable field of view (FOV) produced by the variable holographic-based focal length imaging subsystem of the PLIIM system;

Fig. 9 is a perspective view of an automated tunnel-type laser scanning package identification and weighing system constructed in accordance with the first illustrated embodiment of the present invention, wherein packages, arranged in a non-singulated or singulated configuration, are transported along a high speed conveyor belt, dimensioned by the LADAR-based imaging, detecting and dimensioning subsystem of the present invention, weighed by a weighing scale, and identified by an automatic bar code symbol reading system employing a 1-D (i.e. linear) CCD-based scanning array below which a light focusing lens is mounted for imaging bar coded packages transported therebeneath and decode processing to read such bar code symbols in a fully automated manner without human intervention;

Fig. 10 is a schematic block diagram illustrating the subsystem components of the automated tunnel-type package identification and measurement system of Fig. 9, namely its LADAR-based package imaging, detecting and dimensioning subsystem, package velocity computation subsystem, the package-in-tunnel indication subsystem, the package-out-of-tunnel subsystem, the package weighing-in-motion subsystem, the 1-D (i.e. linear) CCD-based bar code symbol reading subsystem, the data-element queuing, handling and processing subsystem, the input/output port multiplexing subsystem, and the conveyor belt subsystem integrated together as shown;

Fig. 11 is a perspective view of an automated tunnel-type laser scanning package identification and weighing system constructed in accordance with the second illustrated embodiment of the present invention, wherein packages, arranged in a non-singulated singulated configuration, are transported along a high speed conveyor belt, dimensioned by the LADAR-based package imaging, detecting and dimensioning subsystem, weighed by the in-weighing subsystem, and identified PLIIM system of the present invention utilizing low and high resolution CCD image detection arrays for label detection and bar code reading, respectively:

Fig. 12 is a is a schematic block diagram illustrating the subsystem components of the automated tunnel-type package identification and measurement system of Fig. 11, namely its LADAR-based package imaging, detecting and dimensioning subsystem, package velocity computation subsystem, the package-in-tunnel indication subsystem, the package-out-of-tunnel subsystem, the package weighing-in-motion subsystem, the 2-D CCD-based bar code symbol reading subsystem, the data-element queuing, handling and processing subsystem, the input/output port multiplexing subsystem, and the conveyor belt subsystem integrated together as shown;

Fig. 13 is a schematic representation of a third illustrative embodiment of the unitary package dimensioning and identification system of the present invention, embodying the PLIIM

subsystem of the present invention as well as the laser dimensioning and profiling (LDIP) subsystem within a single housing of compact construction;

Fig. 14A is a cross-sectional view of the unitary package dimensioning and identification system of the third illustrative embodiment, taken along line 14A-14A in Fig. 13, showing the PLIIM subsystem contained within a first optically isolated compartment formed the unitary system housing, and the LDIP subsystem contained within a second optically isolated compartment formed therein, wherein a first set of spatially registered light transmission apertures are formed through the panels of both the first and second cavities to enable the PLIIM system to project its planar laser illumination beams towards a target object to be illuminated and collect and receive laser return light off the illuminated object, and wherein a second set of light transmission apertures, optically isolated from the first set of light transmission apertures, are formed in the second cavity to enable the LDIP subsystem to project its dual amplitude-modulated laser beams towards a target object to be dimensioned and profiled, and also to collect and receive laser return light reflected off the illuminated target object;

Fig. 14B is a cross-sectional view of the unitary package dimensioning and identification system of the third illustrative embodiment, taken along line 14B-14B in Fig. 13, showing the spatial layout of the various optical and electro-optical components mounted on the optical bench of the PLIIM subsystem installed within the first cavity of the system housing;

Fig. 15 is a schematic representation of the dual cavity construction of the system housing used to construct the unitary package dimensioning and identification system of the third illustrative embodiment shown in Figs. 13, 14A and 14B, illustrating the that each cavity has its own optical bench, and set of light transmission apertures;

Fig. 16 is a schematic representation of the unitary (PLIIM-based) package dimensioning and identification system of the third illustrative embodiment, showing the various information signals generated by the LDIP subsystem. and provided to the camera control (computer) subsystem), and how the camera control computer generates digital camera control signals which are provided to the image formation and detection (IFD subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner. including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity. (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either a image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user;

Fig. 17 is a schematic representation of a fourth illustrative embodiment of the unitary package dimensioning and identification system of the present invention, embodying the PLIIM subsystem of the present invention as well as the laser dimensioning and profiling (LDIP) subsystem within a single housing of compact construction;

Fig. 18A is a cross-sectional view of the unitary package dimensioning and identification system of the fourth illustrative embodiment, taken along line 18A-18A in Fig. 17, showing the

PLIIM subsystem and its components contained within a first optically isolated compartment formed the unitary system housing, and the LDIP subsystem contained within a second optically isolated compartment formed therein, wherein a first set of spatially registered light transmission apertures are formed through the panels of both the first and second cavities to enable the PLIIM system to project its planar laser illumination beams towards a target object to be illuminated and collect and receive laser return light off the illuminated object, and wherein a second set of light transmission apertures, optically isolated from the first set of light transmission apertures, are formed in the second cavity to enable the LDIP subsystem to project its dual amplitude-modulated laser beams towards a target object to be dimensioned and profiled, and also to collect and receive laser return light reflected off the illuminated target object;

Fig. 18B is a cross-sectional view of the unitary package dimensioning and identification system of the third illustrative embodiment, taken along line 18B-18B in Fig. 17, showing the spatial layout of the various optical and electro-optical components mounted on the optical bench of the PLIIM subsystem installed within the first cavity of the system housing;

Fig. 18C is a schematic representation of an illustrative implementation of the imaging subsystem contained in the image formation and detection (IFD) module employed in the PLIIM system of Fig. 17, shown comprising a stationary lens system mounted before the stationary linear (CCD-type) image detection array, a first movable lens system for stepped movement relative to the stationary lens system during image zooming operations, and a second movable lens system for stepped movements relative to the first movable lens system and the stationary lens system during image focusing operations;

Fig. 19 a schematic representation of the unitary (PLIIM-based) package dimensioning and identification system of the fourth illustrative embodiment, showing the various information signals generated by the LDIP subsystem, and provided to the camera control (computer) subsystem), and how the camera control computer generates digital camera control signals which are provided to the image formation and detection (IFD subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either a image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user;

Fig. 20 is a schematic representation of the unitary (PLIIM-based) package dimensioning and identification system of the third and fourth illustrative embodiments shown in Figs. 13 and 17, showing the use of a "Real-Time" Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem to automatically process raw data received by the LDIP subsystem and generate, as output, time-stamped data sets that are transmitted to a Camera Control (Computer) Subsystem which automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group

translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 21 is a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem employed in the PLIIM-based systems shown in Figs. 13 and 17, wherein each sampled row of raw range data collected by the LDIP subsystem is processed to produce a data set (containing information data elements representative of the current time-stamp, the current package height, the current position of the left and right edges of the package edges, and the current package velocity) which is then transmitted to the Camera Control (Computer) Subsystem for processing and generation of real-time camera control signals that are transmitted to the Auto-Focus/Auto-Zoom Digital Camera Subsystem;

Fig. 22 is a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Edge Detection Processing Method performed by the Real-Time Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem of PLIIM-based systems shown in Figs. 13 and 17;

Fig. 23 is a schematic representation of the Real-Time Package Height Profiling Method carried out in the flow chart of Fig. 21, and the Real-Time Package Edge Detection Method carried out in the flow chart of Fig. 22;

Figs. 24A and 24B, taken together, set forth a Real-Time Camera Control Process that is carried out within the Camera Control Computer Subsystem employed within the PLIIM-based systems of Figs. 13 and 17, wherein the Camera Control (Computer) Subsystem automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 25 is a schematic representation of the Package Data Buffer structure employed by the Real-Time Package Height Profiling And Edge Detection Processing Module illustrated in Figs. 20, 21, 22, and 23, wherein each current raw data set received by the Real-Time Package Height Profiling And Edge Detection Processing Module is buffered in a row of the Package Data Buffer, and each data element in the raw data set is assigned a fixed column index and variable row index which increments as the raw data set is shifted one index unit as each new incoming raw data set is received into the Package Data Buffer;

Fig. 26. is a schematic representation of the Camera Pixel Data Buffer structure employed by the Auto-Focus/Auto-Zoom Digital Camera Subsystem shown in Fig. 20, wherein each pixel element in each captured image frame is stored in a storage cell of the Camera Pixel Data Buffer, assigned a unique set of pixel indices (i,j);

Fig. 27 is a schematic representation of an exemplary Zoom and Focus Lens Group Position Look-Up Table associated with the Auto-Focus/Auto-Zoom Digital Camera Subsystem used by the Camera Control (Computer) Subsystem of the illustrative embodiment, wherein for a given package height detected by the Real-Time Package Height Profiling And Edge Detection Processing Module, the Camera Control Computer uses the Look-Up Table to determine the precise positions to which the focus and zoom lens groups must be moved by generating and supplying real-time camera control signals to the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 28 is a graphical representation of the focus and zoom lens movement characteristics associated with the zoom and lens groups employed in the illustrative embodiment of the Auto-Focus/Auto-Zoom Digital Camera Subsystem, wherein for a given detected package height, the position of the focus and zoom lens group relative to the Camera's working distance is obtained by finding the points along these characteristics at the specified working distance (i.e. detected package height);

Fig. 29 is a schematic representation of an exemplary Photo-integration Time Period Look-Up Table associated with CCD image detection array employed in the Auto-Focus/Auto-Zoom Digital Camera Subsystem of the PLIIM-based system, wherein for a given detected package height and package velocity, the Camera Control Computer uses the Look-Up Table to determine the precise photo-integration time period for the CCD image detection elements employed within the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 30 is a schematic representation of the four-sided tunnel-type package identification and dimensioning (PID) system constructed by arranging four PLIIM-based PID units shown in Figs. 13 and 17 about a high-speed package conveyor belt subsystem, wherein the LDIP subsystem in the top PID unit is configured to dimension packages transported along the belt, while the bottom PID unit is arranged to view packages through a small gap between conveyor belt sections, and all of the PID units are operably connected to the Ethernet control hub of a local area network (LAN);

Fig. 31 is a schematic system diagram of the tunnel-type system shown in Fig. 30, embedded within a first-type LAN having a Ethernet control hub; and

Fig. 32 is a schematic system diagram of the tunnel-type system shown in Fig. 30, embedded within a second-type LAN having a Ethernet control hub and a Ethernet data switch.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE

EMBODIMENTS OF THE PRESENT INVENTION

Referring to the figures in the accompanying Drawings, the preferred embodiments of the Planar Laser Illumination and (Electronic) Imaging (PLIIM) System of the present invention will be described in great detail, wherein like elements will be indicated using like reference numerals.

Overview of the Planar Laser Illumination And Electronic Imaging (PLIIM) System Of The Present Invention

In accordance with the principles of the present invention, an object (e.g. a bar coded package, textual materials, graphical indicia, etc.) is illuminated by a substantially planar laser illumination beam having substantially-planar spatial distribution characteristics along a planar direction which passes through the field of view (FOV) of an image formation and detection module (e.g. realized within a CCD-type digital electronic camera, or a 35 mm optical-film photographic camera), while images of the illuminated object are formed and detected by the image formation and detection module.

This inventive principle of coplanar laser illumination and image formation is embodied in two different classes of the PLIIM, namely: (1) in PLIIM systems shown in Figs. 1A, 1V1, 2A, 2I1, 3A, and 3J1, wherein the image formation and detection modules in these systems employ linear-type (1-D) image detection arrays; and (2) in PLIIM systems shown in Figs. 4A, 5A and 6A, wherein the image formation and detection modules in these systems employ area-type (2-D) image detection arrays. Among these illustrative systems, those shown in Figs. 1A, 2A and 3A each produce a planar laser illumination beam that is neither scanned nor deflected relative to the system housing during planar laser illumination and image detection operations and thus can be said to use "stationary" planar laser illumination beams to read relatively moving bar code symbol structures and other graphical indicia. Those systems shown in Figs. 1V1, 2I1, 3J1, 4A, 5A and 6A, each produce a planar laser illumination beam that is scanned (i.e. deflected) relative to the system housing during planar laser illumination and image detection operations and thus can be said to use "moving" planar laser illumination beams to read relatively stationary bar code symbol structures and other graphical indicia.

In each such system embodiment, it is preferred that each planar laser illumination beam is focused so that the minimum beam width thereof (e.g. 0.6 mm along its non-spreading direction, as shown in Fig. 1I2) occurs at a point or plane which is the farthest or maximum working (i.e. object) distance at which the system is designed to acquire images of objects, as best shown in Fig. 1I2. Hereinafter, this aspect of the present invention shall be deemed the "Focus Beam At Farthest Object Distance (FBAFOD)" principle.

In the case where a fixed focal length imaging subsystem is employed in the PLIIM system, the FBAFOD principle helps compensate for decreases in the power density of the incident planar laser illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem.

In the case where a variable focal length (i.e. zoom) imaging subsystem is employed in the PLIIM system, the FBAFOD principle helps compensate for (i) decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser planar illumination beam of the present invention.

By virtue of the present invention, scanned objects need only be illuminated along a single plane which is coplanar with a planar section of the field of view of the image formation and detection module (e.g. camera) during illumination and imaging operations carried out by the PLIIM system. This enables the use of low-power, light-weight, high-response, ultra-compact, high-efficiency solid-state illumination producing devices, such as visible laser diodes (VLDs), to selectively illuminate ultra-narrow sections of an object during image formation and detection operations, in contrast with high-power, low-response, heavy-weight, bulky, low-efficiency lighting equipment (e.g. sodium vapor lights) required by prior art illumination and image detection systems. In addition, the planar laser illumination techniques of the present invention enables high-speed modulation of the planar laser illumination beam, and use of simple (i.e. substantially-monochromatic wavelength) lens designs for substantially-monochromatic optical illumination and image formation and detection operations.

As will be illustrated in greater detail hereinafter, PLIIM systems embodying the "planar laser illumination" and "FBAFOD" principles of the present invention can be embodied within a wide variety of bar code symbol reading and scanning systems, as well as optical character, text, and image recognition systems well known in the art.

In general, bar code symbol reading systems can be grouped into at least two general scanner categories, namely: industrial scanners; and point-of-sale (POS) scanners.

An industrial scanner is a scanner that has been designed for use in a warehouse or shipping application where large numbers of packages must be scanned in rapid succession. Industrial scanners include conveyor-type scanners, and hold-under scanners. These scanner categories will be described in greater detail below

Conveyor scanners are designed to scan packages as they move by on a conveyor belt. In general, a minimum of six conveyors (e.g. one overhead scanner, four side scanners, and one bottom scanner) are necessary to obtain complete coverage of the conveyor belt and ensure that any label will be scanned no matter where on a package it appears. Conveyor scanners can be further grouped into top, side, and bottom scanners which will be briefly summarized below.

Top scanners are mounted above the conveyor belt and look down at the tops of packages transported therealong. It might be desirable to angle the scanner's field of view slightly in the direction from which the packages approach or that in which they recede depending on the shapes of the packages being scanned. A top scanner generally has less severe depth of field and variable focus or dynamic focus requirements compared to a side scanner as the tops of packages are usually fairly flat, at least compared to the extreme angles that a side scanner might have to encounter during scanning operations.

Side scanners are mounted beside the conveyor belt and scan the sides of packages transported therealong. It might be desirable to angle the scanner's field of view slightly in the

direction from which the packages approach or that in which they recede depending on the shapes of the packages being scanned and the range of angles at which the packages might be rotated.

Side scanners generally have more severe depth of field and variable focus or dynamic focus requirements compared to a top scanner because of the great range of angles at which the sides of the packages may be oriented with respect to the scanner (this assumes that the packages can have random rotational orientations; if an apparatus upstream on the on the conveyor forces the packages into consistent orientations, the difficulty of the side scanning task is lessened). Because side scanners can accommodate greater variation in object distance over the surface of a single target object, side scanners can be mounted in the usual position of a top scanner for applications in which package tops are severely angled.

Bottom scanners are mounted beneath the conveyor and scans the bottoms of packages by looking up through a break in the belt that is covered by glass to keep dirt off the scanner. Bottom scanners generally do not have to be variably or dynamically focused because its working distance is roughly constant, assuming that the packages are intended to be in contact with the conveyor belt under normal operating conditions. However, boxes tend to bounce around as they travel on the belt, and this behavior can be amplified when a package crosses the break, where one belt section ends and another begins after a gap of several inches. For this reason, bottom scanners must have a large depth of field to accommodate these random motions. to which a variable or dynamic focus system could not react quickly enough.

Hold-under scanners are designed to scan packages that are picked up and held underneath it. The package is then manually routed or otherwise handled, perhaps based on the result of the scanning operation. Hold-under scanners are generally mounted so that its viewing optics are oriented in downward direction, like a library bar code scanner. Depth of field (DOF) is an important characteristic for hold-under scanners, because the operator will not be able to hold the package perfectly still while the image is being acquired.

Point-of-sale (POS) scanners are typically designed to be used at a retail establishment to determine the price of an item being purchased. POS scanners are generally smaller than industrial scanner models, with more artistic and ergonomic case designs. Small size, low weight, resistance to damage from accident drops and user comfort are all major design factors for POS scanner. POS scanners include hand-held scanners, hands-free presentation scanners and combination-type scanners supporting both hands-on and hands-free modes of operation. These scanner categories will be described in greater detail below.

Hand-held scanners are designed to be picked up by the operator and aimed at the label to be scanned.

Hands-free presentation scanners are designed to remain stationary and have the item to be scanned picked up and passed in front of the scanning device. Presentation scanners can be mounted on counters looking horizontally, embedded flush with the counter looking vertically. or partially embedded in the counter looking vertically, but having a "tower" portion which rises out above the counter and looks horizontally to accomplish multiple-sided scanning. If necessary, presentation scanners that are mounted in a counter surface can also include a scale to measure weights of items.

Some POS scanners can be used as handheld units or mounted in stands to serve as presentation scanners, depending on which is more convenient for the operator based on the item that must be scanned.

Various generalized embodiments of the PLIIM system of the present invention will now be described in great detail, and after each generalized embodiment, various applications thereof will be described.

First Generalized Embodiment Of The PLIIM System Of The Present Invention

The first generalized embodiment of the PLIIM system of the present invention 1 is illustrated in Fig. 1A. As shown therein, the PLIIM system 1 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) 3 including a 1-D electronic image detection array 3A, and a linear (1-D) imaging subsystem (LIS) 3B having a fixed focal length, a fixed focal distance, and a fixed field of view (FOV), for forming a 1-D image of an illuminated object 4 located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B , each mounted on opposite sides of the IFD module 3. such that each planar laser illumination array 6A and 6B produces a plane of laser beam illumination 7A, 7B which is disposed substantially coplanar with the field view of the image formation and detection module 3 during object illumination and image detection operations carried out by the PLIIM system.

An image formation and detection (IFD) module 3 having an imaging lens with a fixed focal length has a constant angular field of view (FOV); that is, the imaging subsystem can view more of the target object's surface as the target object is moved further away from the IFD module. A major disadvantage to this type of imaging lens is that the resolution of the image that is acquired, expressed in terms of pixels or dots per inch (dpi), varies as a function of the distance from the target object to the imaging lens. However, a fixed focal length imaging lens is easier and less expensive to design and produce than a zoom-type imaging lens which will be discussed in detail hereinbelow with reference to Figs. 3A through 3J4.

The distance from the imaging lens 3B to the image detecting (i.e. sensing) array 3A is referred to as the image distance. The distance from the target object 4 to the imaging lens 3B is called the object distance. The relationship between the object distance (where the object resides) and the image distance (at which the image detection array is mounted) is a function of the characteristics of the imaging lens, and assuming a thin lens, is determined by the thin (imaging) lens equation (1) defined below in greater detail. Depending on the image distance, light reflected from a target object at the object distance will be brought into sharp focus on the detection array plane. If the image distance remains constant and the target object is moved to a new object distance, the imaging lens might not be able to bring the light reflected off the target object (at this new distance) into sharp focus. An image formation and detection (IFD) module having an imaging lens with fixed focal distance cannot adjust its image distance to compensate

for a change in the target's object distance; all the component lens elements in the imaging subsystem remain stationary. Therefore, the depth of field (DOF) of the imaging subsystems alone must be sufficient to accommodate all possible object distances and orientations. Such basic optical terms and concepts will be discussed in more formal detail hereinafter with reference to Figs. 1J1 and 1J6.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B , the linear image formation and detection module 3 , and any non-moving FOV and/or planar laser illumination beam folding mirrors employed in any particular system configuration described herein, are fixedly mounted on an optical bench 8 or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3 and any stationary FOV folding mirrors employed therewith; and (ii) each planar laser illumination array (i.e. VLD/cylindrical lens assembly) 6A, 6B and any planar laser illumination beam folding mirrors employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3, as well as be easy to manufacture, service and repair. Also, this PLIIM system 1 employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

The first illustrative embodiment of the PLIIM system 1A of Fig. 1A is shown in Fig. 1B1. As illustrated therein, the field of view of the image formation and detection module 3 is folded in the downwardly direction by a field of view (FOV) folding mirror 9 so that both the folded field of view 10 and resulting first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations. One primary advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3 can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to practiced in a relatively easy manner.

The PLIIM system 1A illustrated in Fig. 1B1 is shown in greater detail in Fig. 1B2. As shown therein, the linear image formation and detection module 3 is shown comprising an imaging subsystem 3B, and a linear array of photo-electronic detectors 3A realized using high-speed CCD technology (e.g. Dalsa IT-P4 Linear Image Sensors, from Dalsa, Inc. located on the WWW at http://www.dalsa.com). As shown, each planar laser illumination array 6A, 6B

comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. For purposes of clarity, each PLIM is indicated by reference numeral. As shown in Figs. 1K1 and 1K2, the relative spacing of each PLIM is such that the spatial intensity distribution of the individual planar laser beams superimpose and additively provide a substantially uniform composite spatial intensity distribution for the entire planar laser illumination array 6A and 6B.

Fig. 1C is a schematic representation of a single planar laser illumination module (PLIM) 11 used to construct each planar laser illumination array 6A, 6B shown in Fig. 1B2. As shown in Fig. 1C, the planar laser illumination beam emanates substantially within a single plane along the direction of beam propagation towards an object to be optically illuminated.

As shown in Fig. 1D, the planar laser illumination module of Fig. 1C, comprises: a visible laser diode (VLD) 13 supported within an optical tube or block 14; a light collimating lens 15 supported within the optical tube 14; and a cylindrical-type lens element 16 configured together to produce a beam of planar laser illumination 12. As shown in Fig. 1E, a focused laser beam 17 from the focusing lens 15 is directed on the input side of the cylindrical lens element 16, and the produced output therefrom is a planar laser illumination beam 12.

As shown in Fig. 1F, the PLIIM system 1A of Fig. 1A comprises: planar laser illumination arrays 6A and 6B, each having a plurality of PLMS 11A through 11F, and each PLIM being driven by a VLD driver circuit 18 well known in the art; linear-type image formation and detection module 3; field of view (FOV) folding mirror 9, arranged in spatial relation with the image formation and detection module 3; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer, including image-based bar code symbol decoding software such as, for example, SwiftDecode™ Bar Code Decode Software, from Omniplanar, Inc., of Princeton, New Jersey (http://www.omniplanar.com); and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Detailed Description Of An Exemplary Realization Of The PLIIM System Shown In Fig. 1B1 Through 1F

Referring now to Figs. 1G1 through 1N2, an exemplary realization of the PLIIM system shown in Figs. 1B1 through 1F will now be described in detail below.

As shown in Figs. 1G1 and 1G2, the PLIIM system 25 of the illustrative embodiment is contained within a compact housing 26 having height, length and width dimensions 45", 21.7", and 19.7" to enable easy mounting above a conveyor belt structure or the like. As shown in Fig. 1G1, the PLIIM system comprises an image formation and detection module 3, a pair of planar

laser illumination arrays 6A, 6B, and a stationary field of view (FOV) folding structure (e.g. mirror, refractive element, or diffractive element) 9, as shown in Figs. 1B1 and 1B2. The function of the FOV folding mirror 9 is to fold the field of view (FOV) of the image formation and detection module 3 in a direction that is coplanar with the plane of laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B respectively. As shown, components 6A, 6B, 3 and 9 are fixedly mounted to an optical bench 8 supported within the compact housing 26 by way of metal mounting brackets that force the assembled optical components to vibrate together on the optical bench. In turn, the optical bench is shock mounted to the system housing using techniques which absorb and dampen shock forces and vibration. The 1-D CCD imaging array 3A can be realized using a variety of commercially available high-speed line-scan camera systems such as, for example, the Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com. Notably, image frame grabber 17, image data buffer (e.g. VRAM) 20, decode image processor 21, and system controller 22 are realized on one or more printed circuit (PC) boards contained within a camera and system electronic module 27 also mounted on the optical bench, or elsewhere in the system housing 26

In general, the linear CCD image detection array (i.e. sensor) 3A has a single row of pixels, each of which measures from several μm to several tens of μm along each dimension. Square pixels are most common, and most convenient for bar code scanning applications, but different aspect ratios are available. In principle, a linear CCD detection array can see only a small slice of the target object it is imaging at any given time. For example, for a linear CCD detection array having 2000 pixels, each of which is 10μm square, the detection array measures 2 cm long by 10μm high. If the imaging lens 3B in front of the linear detection array 3A causes an optical magnification of 10X, then the 2 cm length of the detection array will be projected onto a 20 cm length of the target object. In the other dimension, the 10μm height of the detection array becomes only 100μm when projected onto the target. Since any label to be scanned will typically measure more than a hundred μm or so in each direction, capturing a single image with a linear image detection array will be inadequate. Therefore, in practice, the linear image detection array employed in each of the PLIIM systems shown in Figs. 1A through 3J6 builds up a complete image of the target object by assembling a series of linear (1-D) images, each of which is taken of a different slice of the target object. Therefore, successful use of a linear image detection array in the PLIIM systems shown in Figs. 1A through 3J6 requires relative movement between the target object and the PLIIM system. In general, either the target object is moving and the PLIIM system is stationary, or else the field of view of PLIIM system is swept across a relatively stationary target object, as shown in Figs. 3J1 through 3J4. This makes the linear image detection array a natural choice for conveyor scanning applications.

As shown in Fig. 1G1, the compact housing 26 has a relatively long light transmission window 28 of elongated dimensions for projecting the FOV of the image formation and detection module 3 through the housing towards a predefined region of space outside thereof, within which objects can be illuminated and imaged by the system components on the optical bench 8. Also, the compact housing 26 has a pair of relatively short light transmission apertures 29A and 29B

closely disposed on opposite ends of light transmission window 28, with minimal spacing therebetween, as shown in Fig. 1G1, so that the FOV emerging from the housing 26 can spatially overlap in a coplanar manner with the substantially planar laser illumination beams projected through transmission windows 29A and 29B, as close to transmission window 28 as desired by the system designer, as shown in Figs. 1G3 and 1G4. Notably, in some applications, it is desired for such coplanar overlap between the FOV and planar laser illumination beams to occur very close to the light transmission windows 20, 29A and 29B (i.e. at short optical throw distances), but in other applications, for such coplanar overlap to occur at large optical throw distances.

In either event, each planar laser illumination array 6A and 6B is optically isolated from the FOV of the image formation and detection module 3. In the preferred embodiment, such optical isolation is achieved by providing a set of opaque wall structures 30A 30B about each planar laser illumination array, from the optical bench 8 to its light transmission window 29A or 29B, respectively. Such optical isolation structures prevent the image formation and detection module 3 from detecting any laser light transmitted directly from the planar laser illumination arrays 6A, 6B within the interior of the housing. Instead, the image formation and detection module 3 can only receive planar laser illumination that has been reflected off an illuminated object, and focused through the imaging subsystem of module 3.

As shown in Fig. 1G3, each planar laser illumination array 6A, 6B comprises a plurality of planar laser illumination modules 11A through 11F, each individually and adjustably mounted to an L-shaped bracket 32 which, in turn, is adjustably mounted to the optical bench. As mentioned above, each planar laser illumination module 11 must be rotatably adjustable within its L-shaped bracket so as permit easy yet secure adjustment of the position of each PLIM 11 along a common alignment plane extending within L-bracket portion 32A thereby permitting precise positioning of each PLIM relative to the optical axis of the image formation and detection module 3. Once properly adjusted in terms of position on the L-bracket portion 32A, each PLIM can be securely locked by an allen or like screw threaded into the body of the L-bracket portion 32A. Also, L-bracket portion 32B, supporting a plurality of PLIMS 11A through 11B, is adjustably mounted to the optical bench 8 and releasably locked thereto so as to permit precise lateral and/or angular positioning of the L-bracket 32B relative to the optical axis and FOV of the image formation and detection module 3. The function of such adjustment mechanisms is to enable the intensity distributions of the individual PLIMs to be additively configured together along a substantially singular plane, typically having a width or thickness dimension on the orders of the width and thickness of the spread or dispersed laser beam within each PLIM. When properly adjusted, the composite planar laser illumination beam will exhibit substantially uniform power density characteristics over the entire working range of the PLIIM system, as shown in Figs. 1K1 and 1K2.

In Fig. 1G3, the exact position of the individual PLIMs 11A through 11F along its L-bracket 32A is indicated relative to the optical axis of the imaging lens 3B within the image formation and detection module 3. Fig. 1G3 also illustrates the geometrical limits of each substantially planar laser illumination beam produced by its corresponding PLIM, measured relative to the folded FOV 10 produced by the image formation and detection module 3. Fig. 1G4, illustrates how, during object illumination and image detection operations, the FOV of the

image formation and detection module 3 is first folded by FOV folding mirror 19, and then arranged in a spatially overlapping relationship with the resulting/composite planar laser illumination beams in a coplanar manner in accordance with the principles of the present invention.

Notably, the PLIIM system of Fig. 1G1 has an image formation and detection module with an imaging subsystem having a fixed focal distance lens and a fixed focusing mechanism. Thus, such a system is best used in either hand-held scanning applications, and/or bottom scanning applications where bar code symbols and other structures can be expected to appear at a particular distance from the imaging subsystem. In Fig. 1G5, the spatial limits for the FOV of the image formation and detection module are shown for two different scanning conditions, namely: when imaging the tallest package moving on a conveyor belt structure; and when imaging objects having height values close to the surface of the conveyor belt structure. In a PLIIM system having a fixed focal distance lens and a fixed focusing mechanism, the PLIIM system would be capable of imaging objects under one of the two conditions indicated above, but not under both conditions. In a PLIIM system having a fixed focal length lens and a variable focusing mechanism, the system can adjust to image objects under either of these two conditions.

In the PLIIM system of Fig. 1G1, special measures are undertaken to ensure that (i) a minimum safe distance is maintained between the VLDs in each PLIM and the user's eyes, and (ii) the planar laser illumination beam is prevented from directly scattering into the FOV of the image formation and detection module, from within the system housing, during object illumination and imaging operations. Condition (i) above can be achieved by using a light shield 32A or 32B shown in Figs. 1G6 and 1G7, respectively, whereas condition (ii) above can be achieved by ensuring that the planar laser illumination beam from the PLIAs and the field of view (FOV) of the imaging lens (in the IFD module) do not spatially overlap on any optical surfaces residing within the PLIIM system. Instead, the planar laser illumination beams are permitted to spatially overlap with the FOV of the imaging lens only outside of the system housing, measured at a particular point beyond the light transmission window 28, through which the FOV 10 is projected to the exterior of the system housing, to perform object imaging operations.

Detailed Description Of The Planar Laser Illumination Modules (PLIMs) Employed In The Planar Laser Illumination Arrays (PLIAs) Of The Illustrative Embodiments

Referring now to Figs. 1G8 through 1I2, the construction of each PLIM 14 and 15 used in the planar laser illumination arrays (PLIAs) will now be described in greater detail below.

As shown in Fig. 1G8, each planar laser illumination array (PLIA) 6A, 6Bemployed in the PLIIM system of Fig. 1G1, comprises an array of planar laser illumination modules (PLIMs) 11 mounted on the L-bracket structure 32, as described hereinabove. As shown in Figs. 1G9 through 1G11, each PLIM of the illustrative embodiment disclosed herein comprises an assembly of subcomponents: a VLD mounting block 14 having a tubular geometry with a hollow central bore 14A formed entirely therethrough, and a v-shaped notch 14B formed on one end thereof; a visible laser diode (VLD) 13 (e.g. Mitsubishi ML1XX6 Series high-power 658nm

AlGaInP semiconductor laser) axially mounted at the end of the VLD mounting block, opposite the v-shaped notch 14B, so that the laser beam produced from the VLD 13 is aligned substantially along the central axis of the central bore 14A; a cylindrical lens 16, made of optical glass (e.g. borosilicate) or plastic having the optical characteristics specified, for example, in Figs. 1G1 and 1G2, and fixedly mounted within the V-shaped notch 14B at the end of the VLD mounting block 14, using an optical cement or other lens fastening means, so that the central axis of the cylindrical lens 16 is oriented substantially perpendicular to the optical axis of the central bore 14A; and a focusing lens 15, made of central glass (e.g. borosilicate) or plastic having the optical characteristics shown, for example, in Figs. IH and 1H2, mounted within the central bore 14A of the VLD mounting block 14 so that the optical axis of the focusing lens 15 is substantially aligned with the central axis of the bore 14A, and located at a distance from the VLD which causes the laser beam output from the VLD 13 to be converging in the direction of the cylindrical lens 16. Notably, the function of the cylindrical lens 16 is to disperse (i.e. spread) the focused laser beam from focusing lens 15 along the plane in which the cylindrical lens 16 has curvature, as shown in Fig. 1I1while the characteristics of the planar laser illumination beam (PLIB) in the direction transverse to the propagation plane are determined by the focal length of the focusing lens 15, as illustrated in Figs. 1I1 and 1I2.

As will be described in greater detail hereinafter, the focal length of the focusing lens 15within each PLIM hereof is preferably selected so that the substantially planar laser illumination beam produced from the cylindrical lens 16 is focused at the farthest object distance in the field of view of the image formation and detection module 3, as shown in Fig. 1I2, in accordance with the "FBAFOD" principle of the present invention. As shown in the exemplary embodiment of Figs. 1I1 and 1I2, wherein each PLIM has maximum object distance of about 61 inches (i.e. 155 centimeters), and the cross-sectional dimension of the planar laser illumination beam emerging from the cylindrical lens 16, in the non-spreading (height) direction, oriented normal to the propagation plane as defined above, is about 0.15 centimeters and ultimately focused down to about 0.06 centimeters at the maximal object distance (i.e. the farthest distance at which the system is designed to capture images). The behavior of the height dimension of the planar laser illumination beam is determined by the focal length of the focusing lens 15 embodied within the PLIM. Proper selection of the focal length of the focusing lens 15 in each PLIM and the distance between the VLD 13 and the focusing lens 15B indicated by reference No. (D), can be determined using the thin lens equation (1) below and the maximum object distance required by the PLIIM system, typically specified by the end-user. As will be explained in greater detail hereinbelow, this preferred method of VLD focusing helps compensate for decreases in the power density of the incident planar laser illumination beam (on target objects) due to the fact that the width of the planar laser illumination beam increases in length for increasing distances away from the imaging subsystem (i.e. object distances).

After specifying the optical components for each PLIM, and completing the assembly thereof as described above, each PLIM is adjustably mounted to the L bracket position 32A by way of a set of mounting/adjustment screws turned through fine-threaded mounting holes formed thereon. In Fig. 1G10, the plurality of PLIMs 11A through 11F are shown adjustably mounted on the L-bracket at positions and angular orientations which ensure substantially uniform power

density characteristics in both the near and far field portions of the planar laser illumination field produced by planar laser illumination arrays (PLIAs) 6A and 6B cooperating together in accordance with the principles of the present invention. Notably, the relative positions of the PLIMs indicated in Fig. 1G9 were determined for a particular set of a commercial VLDs 13 used in the illustrative embodiment of the present invention, and, as the output beam characteristics will vary for each commercial VLD used in constructing each such PLIM, it is therefore understood that each such PLIM may need to be mounted at different relative positions on the L-bracket of the planar laser illumination array to obtain, from the resulting system, substantially uniform power density characteristics at both near and far regions of the planar laser illumination field produced thereby.

While a refractive-type cylindrical lens element 16 has been shown mounted at the end of each PLIM of the illustrative embodiments, it is understood each cylindrical lens element can be realized using refractive, reflective and/or diffractive technology and devices, including reflection and transmission type holographic optical elements (HOEs) well know in the art and described in detail in International Application No. WO 99/57579 published on November 11, 1999, incorporated herein by reference. The only requirement of the optical element mounted at the end of each PLIM is that it has sufficient optical properties to convert a focusing laser beam transmitted therethrough, into a laser beam which expands or otherwise spreads out only along a single plane of propagation, while the laser beam is substantially unaltered (i.e. neither compressed or expanded) in the direction normal to the propagation plane. As used hereinafter and in the claims, the terms "cylindrical lens", "cylindrical lens element" and "cylindrical optical element (COE)" shall be deemed to embrace all such alternative embodiments of this aspect of the present invention.

Detailed Description Of The Image Formation And Detection Module Employed In The PLIIM System Of The First Generalized Embodiment Of The Present Invention

In Fig. 1J1, there is shown a geometrical model (based on the thin lens equation) for the simple imaging subsystem 3B employed in the image formation and detection module 3 in the PLIIM system of the first generalized embodiment shown in Fig. 1A. As shown in Fig. 11J1, this simple imaging system 3B consists of a source of illumination (e.g. laser light reflected off a target object) and an imaging lens. The illumination source is at an object distance r_0 measured from the center of the imaging lens. In Fig. 1J1, some representative rays of light have been traced from the source to the front lens surface. The imaging lens is considered to be of the converging type which, for ordinary operating conditions, focuses the incident rays from the illumination source to form an image which is located at an image distance r_i on the opposite side of the imaging lens. In Fig. 1J1, some representative rays have also been traced from the back lens surface to the image. The imaging lens itself is characterized by a focal length f, the definition of which will be discussed in greater detail hereinbelow.

For the purpose of simplifying the mathematical analysis, the imaging lens is considered to be a thin lens, that is, idealized to a single surface with no thickness. The parameters f, r_0 and r_i, all of which have units of length, are related by the "thin lens" equation (1) set forth below:

$$\frac{1}{f} = \frac{1}{r_0} + \frac{1}{r_i} \qquad (1)$$

This equation may be solved for the image distance, which yields expression (2)

$$r_i = \frac{fr_0}{r_0 - f} \qquad (2)$$

If the object distance r_0 goes to infinity, then expression (2) reduces to $r_i = f$. length of the imaging lens is the image distance at which light incident on the lens from an infinitely distant object will be focused. Once f is known, the image distance for light from any other object distance can be determined using (2).

Field of View of The Imaging Lens and Resolution of The Detected Image

The basic characteristics of an image detected by the IFD module 3 hereof may be determined using the technique of ray tracing, in which representative rays of light are drawn from the source through the imaging lens and to the image. Such ray tracing is shown in Fig. 1J2. A basic rule of ray tracing is that a ray from the illumination source that passes through the center of the imaging lens continues undeviated to the image. That is, a ray that passes through the center of the imaging lens is not refracted. Thus, the size of the field of view (FOV) of the imaging lens may be determined by tracing rays (backwards) from the edges of the image detection/sensing array through the center of the imaging lens and out to the image plane as shown in Fig. 1J2, where d is the dimension of a pixel, n is the number of pixels on the image detector array in this direction, and W is the dimension of the field of view of the imaging lens. Solving for the FOV dimension W, and substituting for r_i using expression (2) above yields expression (3) as follows:

$$W = \frac{dn(r_0 - f)}{f} \qquad (3)$$

Now that the size of the field of view is known, the dpi resolution of the image is determined. The dpi resolution of the image is simply the number of pixels divided by the dimension of the field of view. Assuming that all the dimensions of the system are measured in meters, the dots per inch (dpi) resolution of the image is given by the expression (4) as follows:

$$dpi = \frac{f}{39.37d(r_0 - f)} \qquad (4)$$

Working Distance and Depth of Field of the Imaging Lens

Light returning to the imaging lens that emanates from object surfaces slightly closer to and farther from the imaging lens than object distance r_0 will also appear to be in good focus on the image. From a practical standpoint, "good focus" is decided by the decoding software 21 used when the image is too blurry to allow the code to be read (i.e. decoded), then the imaging subsystem is said to be "out of focus". If the object distance r_0 at which the imaging subsystem is ideally focused is known, then it can be calculated theoretically the closest and farthest "working distances" of the PLIIM system, given by parameters r_{near} and r_{far}, respectively, at which the system will still function. These distance parameters are given by expression (5) and (6) as follows:

$$r_{near} = \frac{f r_0 (f + DF)}{f^2 + DF r_0} \tag{5}$$

$$r_{far} = \frac{f r_0 (f - DF)}{f^2 - DF r_0} \tag{6}$$

where D is the diameter of the largest permissible "circle of confusion" on the image detection array. A circle of confusion is essentially the blurred out light that arrives from points at image distances other than object distance r_0. When the circle of confusion becomes too large (when the blurred light spreads out too much) then one will lose focus. The value of parameter D for a given imaging subsystem is usually estimated from experience during system design, and then determined more precisely, if necessary, later through laboratory experiment.

Another optical parameter of interest is the total depth of field Δr, which is the difference between distances r_{far} and r_{near}; this parameter is the total distance over which the imaging system will be able to operate when focused at object distance r_0. This optical parameter may be expressed by equation (7) below:

$$\Delta r = \frac{2 D f^2 F r_0 (r_0 - f)}{f^4 - D^2 F^2 r_0^2} \tag{7}$$

It should be noted that the parameter Δr is generally not symmetric about r_0; the depth of field usually extends farther towards infinity from the ideal focal distance than it does back towards the imaging lens.

Modeling A Fixed Focal Length Imaging Subsystem Used In The Image Formation And Detection Module Of The Present Invention

A typical imaging (i.e. camera) lens used to construct a fixed focal-length image formation and detection module of the present invention might typically consist of three to fifteen or more individual optical elements contained within a common barrel structure. The inherent complexity of such an optical module prevents its performance from being described very accurately using a "thin lens analysis", described above by equation (1). However, the results of

a thin lens analysis can be used as a useful guide when choosing an imaging lens for a particular PLIIM system application.

A typical imaging lens can focus light (illumination) originating anywhere from an infinite distance away, to a few feet away. However, regardless of the origin of such illumination, its rays must be brought to a sharp focus at exactly the same location (e.g. the film plane or image detector), which (in an ordinary camera) does not move. At first glance, this requirement may appear unusual because the thin lens equation (1) above states that the image distance at which light is focused through a thin lens is a function of the object distance at which the light originates, as shown in Fig. 1J3. Thus, it would appear that the position of the image detector would depend on the distance at which the object being imaged is located. An imaging subsystem having a variable focal distance lens assembly avoids this difficulty because several of its lens elements are capable of movement relative to the others. For a fixed focal length imaging lens, the leading lens element(s) can move back and forth a short distance, usually accomplished by the rotation of a helical barrel element which converts rotational motion into purely linear motion of the lens elements. This motion has the effect of changing the image distance to compensate for a change in object distance, allowing the image detector to remain in place, as shown in the schematic optical diagram of Fig. 1J4.

Modeling A Variable Focal Length (Zoom) Imaging Lens Used In The Image Formation And Detection Module Of The Present Invention

As shown in Fig. 1J5, a variable focal length (zoom) imaging subsystem has an additional level of internal complexity. A zoom-type imaging subsystem is capable of changing its focal length over a given range; a longer focal length produces a smaller field of view at a given object distance. Consider the case where the PLIIM system needs to illuminate and image a certain object over a range of object distances, but requires the illuminated object to appear the same size in all acquired images. When the object is far away, the PLIIM system will generate control signals that select a long focal length, causing the field of view to shrink (to compensate for the decrease in apparent size of the object due to distance). When the object is close, the PLIIM system will generate control signals that select a shorter focal length, which widens the field of view and preserves the relative size of the object. In many bar code scanning applications, a zoom-type imaging subsystem in the PLIIM system (as shown in Figs. 3A through 3J5) ensures that all acquired images of bar code symbols have the same dpi image resolution regardless of the position of the bar code symbol within the object distance of the PLIIM system.

As shown in Fig. 1J5, a zoom-type imaging subsystem has two groups of lens elements which are able to undergo relative motion. The leading lens elements are moved to achieve focus in the same way as for a fixed focal length lens. Also, there is a group of lenses in the middle of the barrel which move back and forth to achieve the zoom, that is, to change the effective focal length of all the lens elements acting together.

Several Techniques For Accommodating The Field of View (FOV) Of A PLIIM System To Particular End-User Environments

In many applications, a PLIIM system of the present invention may include an imaging subsystem with a very long focal length imaging lens (assembly), and this PLIIM system must be installed in end-user environments having a substantially shorter object distance range, and/or field of view (FOV) requirements or the like. Such problems can exist for PLIIM systems employing either fixed or variable focal length imaging subsystems. To accommodate a particular PLIIM system for installation in such environments, three different techniques illustrated in Figs. 1K1-1K2, 1L1 and 1L2 can be used.

In Figs. 1K1 and 1K2, the focal length of the imaging lens 3B can be fixed and set at the factory to produce a field of view having specified geometrical characteristics for particular applications. In Fig. K1, the focal length of the image formation and detection module 3 is fixed during the optical design stage so that the fixed field of view (FOV) thereof substantially matches the scan field width measured at the top of the scan field, and thereafter overshoots the scan field and extends on down to the plane of the conveyor belt 34. In this FOV arrangement, the dpi image resolution will be greater for packages having a higher height profile above the conveyor belt, and less for envelope-type packages with low height profiles. In Fig. 1K2, the focal length of the image formation and detection module 3 is fixed during the optical design stage so that the fixed field of view thereof substantially matches the plane slightly above the conveyor belt 34 where envelope-type packages are transported. In this FOV arrangement, the dpi image resolution will be maximized for envelope-type packages which are expected to be transported along the conveyor belt structure, and this system will be unable to read bar codes on packages having a height-profile exceeding the low-profile scanning field of the system.

In Fig. 1L, a FOV beam folding mirror arrangement is used to fold the optical path of the imaging subsystem within the interior of the system housing so that the FOV emerging from the system housing has geometrical characteristics that match the scanning application at hand. As shown, this technique involves mounting a plurality of FOV folding mirrors 9A through 9E on the optical bench of the PLIIM system to bounce the FOV of the imaging subsystem 3B back and forth before the FOV emerges from the system housing. Using this technique, when the FOV emerges from the system housing, it will have expanded to a size appropriate for covering the entire scan field of the system. This technique is easier to practice with image formation and detection modules having linear image detectors, for which the FOV folding mirrors only have to expand in one direction as the distance from the imaging subsystem increases. In Fig. 1L, this direction of FOV expansion occurs in the direction perpendicular to the page. In the case of area-type PLIIM systems, as shown in Figs. 4A through 6F4, the FOV folding mirrors have to accommodate a 3-D FOV which expands in two directions. Thus an internal folding path is easier to arrange for linear-type PLIIM systems.

In Fig. 1L2, the fixed field of view of an imaging subsystem is expanded across a working space (e.g. conveyor belt structure) by using a motor 35 to controllably rotate the FOV 10 during object illumination and imaging operations. When designing a linear-type PLIIM system for industrial scanning applications, wherein the focal length of the imaging subsystem is fixed, a higher dpi image resolution will occasionally be required. This implies using a longer focal length imaging lens, which produces a narrower FOV and thus higher dpi image resolution. However, in many applications, the image formation and detection module in the PLIIM system

cannot be physically located far enough away from the conveyor belt (and within the system housing) to enable the narrow FOV to cover the entire scanning field of the system. In this case, a FOV folding mirror 9F can be made to rotate, relative to stationary for folding mirror 9G, in order to sweep the linear FOV from side to side over the entire width of the conveyor belt, depending on where the bar coded package is located. Ideally, this rotating FOV folding mirror 9F would have only two mirror positions, but this will depend on how small the FOV is at the top of the scan field. The rotating FOV folding mirror can be driven by motor 35 operated under the control of the system controller 22, as described herein.

Method of Adjusting the Focal Characteristics of the Planar Laser Illumination Beams Generated by Planar Laser Illumination Arrays Used in Conjunction with Image Formation And Detection Modules Employing Fixed Focal Length Imaging Lenses

In the case of a fixed focal length camera lens, the planar laser illumination beam 7A, 7B is focused at the farthest possible object distance in the PLIIM system. In the case of fixed focal length imaging lens, this focus control technique of the present invention is not employed to compensate for decrease in the power density of the reflected laser beam as a function of $1/r^2$ distance from the imaging subsystem, but rather to compensate for a decrease in power density of the planar laser illumination beam on the target object due to an increase in object distance away from the imaging subsystem.

It can be shown that laser return light that is reflected by the target object (and measured/detected at any arbitrary point in space) decreases in intensity as the inverse square of the object distance. In the PLIIM system of the present invention, the relevant decrease in intensity is not related to such "inverse square" law decreases, but rather to the fact that the width of the planar laser illumination beam increases as the object distance increases. This "beam-width/object-distance" law decrease in light intensity will be described in greater detail below.

Using a thin lens analysis of the imaging subsystem, it can be shown that when any form of illumination having a uniform power density E_0 (i.e. power per unit area) is directed incident on a target object surface and the reflected laser illumination from the illuminated object is imaged through an imaging lens having a fixed focal length f and f-stop F, the power density E_{pix} (measured at the pixel of the image detection array and expressed as a function of the object distance r) is provided by the expression (8) set forth below:

$$E_{pix} = \frac{E_0}{8F}(1 - \frac{f}{r})^2 \qquad (8)$$

Fig. 1M1 shows a plot of pixel power density E_{pix} vs. object distance r calculated using the arbitrary but reasonable values $E_0 = 1$ W/m^2, f = 80 mm and F = 4.5. This plot demonstrates that, in a counter-intuitive manner, the power density at the pixel (and therefore the power incident on the pixel, as its area remains constant) actually increases as the object distance increases. Careful analysis explains this particular optical phenomenon by the fact that the field of view of each pixel on the image detection array increases slightly faster with increases in

object distances than would be necessary to compensate for the $1/r^2$ return light losses. A more analytical explanation is provided below.

The width of the planar laser illumination beam increases as object distance r increases. At increasing object distances, the constant output power from the VLD in each planar laser illumination module (PLIM) is spread out over a longer beam width, and therefore the power density at any point along the laser beam width decreases. To compensate for this phenomenon, the planar laser illumination beam of the present invention is focused at the farthest object distance so that the height of the planar laser illumination beam becomes smaller as the object distance increases; as the height of the planar laser illumination beam becomes narrower towards the farthest object distance, the laser beam power density increases at any point along the width of the planar laser illumination beam. The decrease in laser beam power density due to an increase in planar laser beam width and the increase in power density due to a decrease in planar laser beam height, roughly cancel each other out, resulting in a power density which either remains approximately constant or increases as a function of increasing object distance, as the application at hand may require.

When the laser beam is fanned (i.e. spread) out into a substantially planar laser illumination beam by the cylindrical lens element employed within each PLIM in the PLIIM system, the total output power in the planar laser illumination beam is distributed along the width of the beam in a roughly Gaussian distribution, as shown in the power vs. position plot of Fig. 1M2. Notably, this plot was constructed using actual data gathered with a planar laser illumination beam focused at the farthest object distance in the PLIIM system. For comparison purposes, the data points and a Gaussian curve fit are shown for the planar laser beam widths taken at the nearest and farthest object distances. To avoid having to consider two dimensions simultaneously (i.e. left-to-right along the planar laser beam width dimension and near-to-far through the object distance dimension), the discussion below will assume that only a single pixel is under consideration, and that this pixel views the target object at the center of the planar laser beam width.

For a fixed focal length imaging lens, the width L of the planar laser beam is a function of the fan/spread angle θ induced by (i) the cylindrical lens element in the PLIM and (ii) the object distance r, as defined by the following expression (9):

$$L = 2r \tan \frac{\theta}{2} \qquad (9)$$

Fig. 1M3 shows a plot of beam width length L versus object distance r calculated using θ = 50°, demonstrating the planar laser beam width increases as a function of increasing object distance.

The height parameter of the planar laser illumination beam "h" is controlled by adjusting the focusing lens 15 between the visible laser diode (VLD) 13 and the cylindrical lens 16, shown in Figs. 1I1 and 1I2. Fig. 1M4 shows a typical plot of planar laser beam height h vs. image distance r for a planar laser illumination beam focused at the farthest object distance in accordance with the principles of the present invention. As shown in Fig. 1M4, the height dimension of the planar laser beam decreases as a function of increasing object distance.

Assuming a reasonable total laser power output of 20 mW from the VLD 13 in each PLIM 11, the values shown in the plots of Figs. 1M3 and 1M4 can be used to determine the power density E_0 of the planar laser beam at the center of its beam width, expressed as a function of object distance. This measure, plotted in Fig. 1N, demonstrates that the use of the laser beam focusing technique of the present invention, wherein the height of the planar laser illumination beam is decreased as the object distance increases, compensates for the increase in beam width in the planar laser illumination beam, which occurs for an increase in object distance. This yields a laser beam power density on the target object which increases as a function of increasing object distance over a substantial portion of the object distance range of the PLIIM system.

Finally, the power density E_0 plot shown in Fig. 1N can be used with expression (1) above to determine the power density on the pixel, E_{pix}. This E_{pix} plot is shown in Fig. 1O. For comparison purposes, the plot obtained when using the beam focusing method of the present invention is plotted in Fig. 1O against a "reference" power density plot E_{pix} which is obtained when focusing the laser beam at infinity, using a collimating lens (rather than a focusing lens 15) disposed after the VLD 13, to produce a collimated-type planar laser illumination beam having a constant beam height of 1 mm over the entire portion of the object distance range of the system. Notably, however, this non-preferred beam collimating technique, selected as the reference plot in Fig. 1O, does not compensate for the above-described effects associated with an increase in planar laser beam width as a function of object distance. Consequently, when using this non-preferred beam focusing technique, the power density of the planar laser illumination beam produced by each PLIM decreases as a function of increasing object distance.

Therefore, in summary, where a fixed or variable focal length imaging subsystem is employed in the PLIIM system hereof, the planar laser beam focusing technique of the present invention described above helps compensate for decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing object distances away from the imaging subsystem.

Producing A Composite Planar Laser Illumination Beam Having Substantially Uniform Power Density Characteristics In Near And Far Fields, By Additively Combining The Individual Gaussian Power Density Distributions Of Planar Laser Illumination Beams Produced By Planar Laser Illumination Beam Modules (PLIMS) In Planar Laser Illumination Arrays (PLIAS)

Having described the best known method of focusing the planar laser illumination beam produced by each VLD in each PLIM in the PLIIM system hereof, it is appropriate at this juncture to describe how the individual Gaussian power density distributions of the planar laser illumination beams produced a PLIA 6A, 6B are additively combined to produce a composite planar laser illumination beam having substantially uniform power density characteristics in near and far fields, as illustrated in Figs. 1P1 and 1P2.

When the laser beam produced from the VLD is transmitted through the cylindrical lens, the output beam will be spread out into a laser illumination beam extending in a plane along the direction in which the lens has curvature. The beam size along the axis which corresponds to the height of the cylindrical lens will be transmitted unchanged. When the planar laser illumination

beam is projected onto a target surface, its profile of power versus displacement will have an approximately Gaussian distribution. In accordance with the principles of the present invention, the plurality of VLDs on each side of the IFD module are spaced out and tilted in such a way that their individual power density distributions add up to produce a (composite) planar laser illumination beam having a magnitude of illumination which is distributed substantially uniformly over the entire working depth of the PLIIM system (i.e. along the height and width of the composite planar laser illumination beam).

The actual positions of the PLIMs along each planar laser illumination array are indicated in Fig. 1G3 for the exemplary PLIIM system shown in Figs. 1G1 through 1I2. The mathematical analysis used to analyze the results of summing up the individual power density functions of the PLIMs at both near and far working distances was carried out using the Matlab™ mathematical modeling program by Mathworks, Inc. (http://www.mathworks.com). These results are set forth in the data plots of Figs. 1P1 and 1P2. Notably, in these data plots, the total power density is greater at the far field of the working range of the PLIIM system. This is because the VLDs in the PLIMs are focused to achieve minimum beam width thickness at the farthest object distance of the system, whereas the beam height is somewhat greater at the near field region. Thus, although the far field receives less illumination power at any given location, this power is concentrated into a smaller area, which results in a greater power density within the substantially planar extent of the planar laser illumination beam of the present invention.

When aligning the individual planar laser illumination beams (i.e. planar beam components) produced from each PLIM, it will be important to ensure that each such planar laser illumination beam spatially coincides with a section of the FOV of the imaging subsystem, so that the composite planar laser illumination beam produced by the individual beam components spatially coincides with the FOV of the imaging subsystem throughout the entire working depth of the PLIIM system.

Method Of Substantially Reducing The Power Density Spectrum Of Speckle-Noise Patterns Produced At The Linear Image Detection Array Of A PLIIM System When Illuminating Objects Using A Planar Laser Illumination Beam

When detecting images produced by illuminating target objects with a coherent illumination source as employed in the PLIM of the present invention, "speckle"(i.e. substrate or paper) noise is generated and detected at the CCD-type electronic image detection array, severely reducing the signal-to-noise (SNR) ratio of the IFD module. The problem of speckle levels and patterns in laser scanning systems is analyzed in the (25 slide) paper entitled "Speckle Noise and Laser Scanning Systems" by Sasa Kresic-Juric, Emanuel Marom and Leonard Bergstein, of Symbol Technologies, Holtsville, NY, published at http://www.ima.umn.edu/industrial/99-2000/kresic/sld001.htm. However, this publication fails to provide any technically feasible solution, or offer any techniques that might be used in the PLIIM-based systems disclosed herein to mitigate the power density spectrum of speckle-noise patterns generated within the electronic image detection arrays employed therein.

There are many devices that could be used to achieve the desired phase shifting operations required by the technique of the present invention. Such devices include, but are not limited to, moving phase-screens, tilting or micro-oscillating mirrors, defocusing elements, deformable mirrors, acousto-optical and electro-optical phase modulators. In general, the response time characteristics of such devices will be set based on several factors including: (1) the degree of speckle amplitude reduction required by the application at hand; and (2) the photo-integration time period ($\Delta T_{photo-integration}$) the image detection elements in the IFD module, which will be typically set by other considerations (e.g. ensuring that detected pixels are square to satisfy requirements of image-based bar code symbol decoders and/or OCR processors employed in the PLIIM-based system) .

Fig. 1G13 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by a refractive-type cylindrical lens array that is micro-oscillated by a pair of ultrasonic transducers arranged in a push-pull configuration. This mechanism is operated so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G14 shows the refractive-type cylindrical lens array employed in the optical assembly shown in Fig. 1G13.

Fig. 1G15 shows the array support frame employed in the optical assembly shown in Fig. 1G13.

Fig. 1G16 shows the refractive-type cylindrical lens array employed in Fig. 1G13. illustrated as configured between a pair of ultrasonic transducers operated in a push-pull mode of operation.

Conditions For Destroying Spatial Coherence Of The Laser Beam Illumination Sources In The PLIM Of The Present Invention

To destroy the spatial coherence of the laser beam illumination sources, and achieve a significant reduction in speckle-noise pattern at the image detection array, the individual beam components within the composite planar laser illumination beam should be micro-oscillated (i.e. moved) along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) the rate of change of

such beam component movement should be greater than or equal to the inverse of the photo-integration time period of the detector elements in the image detector array.

The first condition above can derived by taking the case example, where two virtual laser illumination sources (such as those generated by the cylindrical lens array) are illuminating a target object as shown in Fig. 1G13A. In this case, the speckle noise pattern viewed by the elements of the imaging array will become uncorrelated with the original speckle pattern (produced by the real laser illumination source) when a difference in phase among the wavefronts of the individual beam component is on the order of 1/2 of the laser illumination wavelength. For the case of a moving cylindrical lens array, as shown in Fig. 1G13A, this is equivalent to the condition

$$\Delta x > \lambda D / 2 P$$

where Δx is the motion, λ is the characteristic wavelength of the laser illumination source, D is the distance from the laser diode (i.e. source) to the cylindrical lens array, and P is the separation of the lenslets within the lens array. This implies that speckle noise patterns viewed by the detector elements of the imaging array will become uncorrelated with the original speckle pattern (produced by the real laser illumination source) when there is a spatial gradient in the phase of the beam wavefronts on the order of $\lambda/2P$.

To ensure that the uncorrelated speckle-noise patterns detected at the image detection array can additively cancel out, the rate of change of such beam component movement (i.e. first derivative of Δx) should be greater than or equal to the inverse of the photo-integration time period of the detector elements in the image detector array (i.e. $1/\Delta T_{photo-integration}$). In the case of Fig. 1G13A, this implies the frequency of micro-oscillation of the cylindrical lens array should be greater than or equal to the inverse of the photo-integration time period of the detector elements in the image detector array (i.e. $1/\Delta T_{photo-integration}$). By ensuring the conditions are satisfied to the best degree possible will ensure optimal reduction in speckle-noise patterns produced the image detector of the PLIIM-based system of the present invention. Figs. 1G13B1 and 1G13B2 illustrate that significant mitigation in speckle-noise patterns cane be achieved when using the principles of the present invention taught herein.

Fig. 1G17 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by (a holographically-fabricated) diffractive-type cylindrical lens array that is micro-oscillated by a pair of ultrasonic transducers arranged in a push-pull configuration. This mechanism is operated so as to micro-oscillate (i.e. move) each individual beam component within the composite planar laser illumination beam along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration period

of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G18 shows the refractive-type cylindrical lens array employed in the optical assembly shown in Fig. 1G17.

Fig. 1G19 shows the array support frame employed in the optical assembly shown in Fig. 1G17.

Fig. 1G20 shows the refractive-type cylindrical lens array employed in Fig. 1G17, illustrated as configured between a pair of ultrasonic transducers operated in a push-pull mode of operation.

Fig. 1G21 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by a stationary reflective element fixedly mounted in front of a refractive-type cylindrical lens array, and a pair of micro-oscillating reflective elements that are micro-oscillated about a common pivot point by a pair of ultrasonic transducers arranged in a push-pull configuration. This mechanism is operated so that each individual beam component within the composite planar laser illumination beam is micro-oscillated (i.e. moved) along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1 2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G22 shows the pair of micro-oscillating reflective elements employed in the optical assembly shown in Fig. 1G21.

Fig. 1G23 shows the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated.

Fig. 1G24 shows one micro-oscillating reflective element in the pair employed in Fig. 1G21, illustrated as configured between a pair of ultrasonic transducers operated in a push-pull mode of operation, so as to undergo micro-oscillation.

Fig. 1G25 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by an acousto-optical (i.e. Bragg Cell) beam deflection device through which each laser beam within the PLIM is transmitted and deflected in response to acoustical signals propagating through the electro-acoustical device. This mechanism is operated so that each individual beam component within the composite planar laser illumination beam is micro-oscillated (i.e. moved) along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the

individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G26 shows the optical path which each laser beam within the PLIM travels on its way towards a target object to be illuminated.

Fig. 1G27 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB micro-oscillation mechanism realized by (i) a piezo-electrically driven deformable mirror (DM) structure arranged in front of a stationary cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), and (ii) a stationary beam folding mirror. This mechanism is operated so that the surface of the DM structure is periodically deformed at frequencies in the 100kHz range and at few microns amplitude so that the reflective surface thereof exhibits moving ripples aligned along the direction that is perpendicular to planar extent of the planar laser illumination beam (i.e. along laser beam spread). In turn, each individual beam component within the composite planar laser illumination beam is micro-oscillated (i.e. moved) along the planar extent thereof (i) by an amount of distance Δx which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change of such beam component movement is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different points in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the spatial coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat. Since the DM is capable of accepting drive signals of up to 100V, ideally about 30 independent speckle realizations can be produced leading to a reduction in speckle noise amplitude by factor of at least 5.

Fig. 1G28 shows the stationary beam folding mirror structure employed in the optical assembly shown in Fig. 1G27.

Fig. 1G29 shows the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated while undergoing phase modulation by the piezo-electrically driven deformable mirror structure.

<u>Methods And Apparatus Are Disclosed For Destroying The Spatial Coherence Of The Laser Illumination Sources Employed In The PLIMs Of The Present Invention</u>

The manner in which the "temporal" coherence of the illumination sources is destroyed is by creating multiple "virtual" illumination sources that illuminate the object at different moments in time, over the photo-integration time period of the electronic image detection array used in the IFD module. When using this method, the wavefront of the individual beam components within the composite planar laser illumination beam are (i) either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta\phi$ (for the case of PM) which is sufficient to cause a difference in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) at a rate of change (in such wavefront modulation) which is greater than or equal to the inverse of the photo-integration time period of the detector elements. Under such conditions, the target object is repeatedly illuminated with laser light apparently originating from different moments in time over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. On a time-average basis, the coherent addition of laser illumination from such moving virtual illumination sources, causes a change in the illumination field detected at each image detection element in the IFD module. This destroys the temporal coherence of the laser illumination beam received at the detector elements and thereby reduces the speckle-noise pattern (i.e. level) produced thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle noise amplitude should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof. Image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

Fig. 1G30 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB modulation mechanism realized by a high-speed laser beam amplitude modulation structure (e.g. electro-optical gating device) arranged in front of the cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles). This mechanism is operated so that (i) the wavefront of each individual beam component within the composite planar laser illumination beam is either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta\phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an

amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change in such wavefront modulation is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different moments in time over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the temporal coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G31 shows the optical path which each optically-gated laser beam within the PLIM travels on its way towards the target object to be illuminated.

Conditions For Destroying Temporal Coherence Of The Laser Beam Illumination Sources In The PLIM Of The Present Invention

To destroy the temporal coherence of the laser beam illumination sources, and achieve a significant reduction in speckle-noise pattern at the image detection array, the wavefront of individual beam components within the composite planar laser illumination beam should be wherein (i) either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta \phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) the rate of change in such wavefront modulation should be greater than or equal to the inverse of the photo-integration time period of the detector elements.

There are several techniques for destroying the temporal coherence of the laser. The most straightforward is achieved by modulation of the laser, either by modulating the diode current or by use of an external optical modulator. Amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM) techniques can be employed. The primary effect of such modulation is to introduce side-bands into the optical spectrum of the laser illumination beam. The frequencies of this side-band spectra are given by the sum and difference frequencies of the optical carrier and the modulation frequency employed.

Speckle noise is produced at the image detector by coherent interference of light reflected from nearby points on the target surface. If the laser modulation frequency is changed at a sufficiently high rate, the light reflected from two points on the surface will be illuminated by light of different frequencies. This is due to the difference in optical path length from the laser to the two points. If the difference in frequencies is large compared to the photo-integration time of the imaging array, then the speckle noise pattern will appear to be washed out (i.e. additively cancelled) by the beating of the two optical frequencies. The rate of change of the wavefront modulation thus depends upon the character of the surface (specifically on the separation in optical path length of typical illumination sources and the size of the resolution element of the imager).

Temporal coherence of the laser illumination sources may also be destroyed by delaying a portion of the laser light emitted by the laser by a time longer than the inherent temporal coherence of the laser. Typical laser diodes have a coherence length of a few centimeters (cm). Thus, if some of the laser illumination can be delayed by the time of flight of a few cm, then it will be incoherent with the original laser illumination. One method for achieving this is via an etalon. This electrically-passive device, shown in Figs. 32 and 33, can be realized by a pair of parallel, reflective surfaces, mounted to the output of each VLD in the PLIA. If one surface is essentially totally reflective and the other, e.g., 97% reflective, then about 3% of the laser illumination will escape the device through the partially reflective surface of the device on each round trip. The laser illumination will be delayed by the time of flight for one round trip between the plates. If the plates are separated by several centimeters, then this delay will be greater than the coherence time of the laser source. For the example given, the light will make about 30 trips between the plates. This would have the effect of mixing 30 samples from the laser source, each sample residing outside the coherence time thereof, thus destroying the temporal coherence of the laser illumination sources in the PLIM of the present invention. A primary advantage of this technique is that it employs electrically-passive components which might be manufactured relatively inexpensively in mass-production environment.

To ensure that the uncorrelated speckle-noise patterns detected at the image detection array can additively cancel out, the rate of change of such beam component modulation (i.e. first derivative of Δ m, f or ϕ) should be greater than or equal to the inverse of the photo-integration time period of the detector elements in the image detector array (i.e. $1/\Delta T_{photo-integration}$). By ensuring these conditions are satisfied to the best degree possible will ensure optimal reduction in speckle-noise patterns produced the image detector of the PLIIM-based system of the present invention.

Fig. 1G32 shows an optical assembly comprising the PLIA of Fig. 1G8 and a PLIB modulation mechanism realized by a high-frequency optically resonant arranged in front of the cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), as described above. In this mechanism, (i) the wavefront of each individual beam component within the composite planar laser illumination beam is either amplitude modulated (AM) at a depth of modulation Δm (for case of AM), frequency modulated (FM) by an amount of frequency shift Δf (for the case of FM) or phase modulated (PM) by an amount of phase shift $\Delta\phi$ (for the case of PM) which is sufficient to cause a different in phase among the wavefronts of the individual beam component by an amount on the order of 1/2 of the laser illumination wavelength, and (ii) wherein the rate of change in such wavefront modulation is greater than or equal to the inverse of the photo-integration time period of the detector elements. By performing such operation, the target object is repeatedly illuminated with laser light apparently originating from different moments in time over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element, thereby destroying the temporal coherence of the laser illumination beam received at the detector element and reducing the speckle-noise pattern (i.e. level) produced thereat.

Fig. 1G33 shows the optical path which each optically-gated laser beam within the PLIM travels on its way towards a target object to be illuminate.

Second Alternative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1Q1, the second illustrative embodiment of the PLIIM system of Figs. 1A is shown comprising: a 1-D type image formation and detection (IFD) module 3', as shown in Fig. 1B1; and a pair of planar laser illumination arrays 6A and 6B . As shown, these arrays 6A and 6B are arranged in relation to the image formation and detection module 3 so that the field of view thereof is oriented in a direction that is coplanar with the planes of laser illumination produced by the planar illumination arrays, without using any laser beam or field of view folding mirrors. One primary advantage of this system architecture is that it does not require any laser beam or FOV folding mirrors, employs the few optical surfaces, and maximizes the return of laser light, and is easy to align. However, it is expected that this system design will most likely require a system housing having a height dimension which is greater than the height dimension required by the system design shown in Fig. 1B1.

As shown in Fig. 1Q2, PLIIM system 1Bshown in Fig. 1Q1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1P1 and 102 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Third Alternative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1R1, the third illustrative embodiment of the PLIIM system of Figs. 1A, 1C are shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam

folding mirrors 37A and 37B arranged. The function of the planar laser illumination beam folding mirrors 37A and 37B is to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B such that the field of view (FOV) of the image formation and detection module 3 is aligned in a direction that is coplanar with the planes of first and second planar laser illumination beams during object illumination and imaging operations. One notable disadvantage of this system architecture is that it requires additional optical surfaces which can reduce the intensity of outgoing laser illumination and therefore reduce slightly the intensity of returned laser illumination reflected off target objects. Also this system design requires a more complicated beam/FOV adjustment scheme, than not using any planar laser illumination beam folding mirrors. This system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. In this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors, and cylindrical lenses with larger radiuses will be employed in the design of each PLIM.

As shown in Fig. 1R2, PLIIM system 1C shown in Fig. 1R1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 6A through 6B, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; pair of planar laser beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1Q1 and 1Q2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1S1, the fourth illustrative embodiment of the PLIIM system of Figs. 1A, indicated by reference No. 1D is shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; a

field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3 about 90 degrees downwardly; and a pair of planar laser beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B such that the planes of first and second planar laser illumination beams 7A and 7B are in a direction that is coplanar with the field of view of the image formation and detection module 3. Despite inheriting most of the disadvantages associated with the system designs shown in Figs. 1B1 and 1R1, this system architecture allows the length of the system housing to be easily minimized, at the expense of an increase in the height and width dimensions of the system housing.

As shown in Fig. 1S2, PLIIM system 1D shown in Fig. 1S1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3; a pair of planar laser beam folding mirrors 9 and 3 arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1S1 and 1S2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Applications For The First Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

Fixed focal distance PLIIM systems shown in Figs. 1B1 through 1U are ideal for applications in which there is little variation in the object distance, such as in a conveyor-type bottom scanner application. As such scanning systems employ a fixed focal length imaging lens, the image resolution requirements of such applications must be examined carefully to determine that the image resolution obtained is suitable for the intended application. Because the object distance is approximately constant for a bottom scanner application (i.e. the bar code almost always is illuminated and imaged within the same object plane), the dpi resolution of acquired images will be approximately constant. As image resolution is not a concern in this type of

scanning applications, variable focal length (zoom) control is unnecessary, and a fixed focal length imaging lens should suffice and enable good results.

A fixed focal distance PLIIM system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM systems are good choices for handheld and presentation scanners as indicated in Fig. 1U, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to a twelve or

more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length camera lens, the variation in object distance implies that the dots per inch resolution of the image will vary as well. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM system.

Second Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging System Of The Present Invention

The second generalized embodiment of the PLIIM system of the present invention 1' is illustrated in Figs. 1V1 and 1V2. As shown in Fig. 1V1, the PLIIM system 1' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a moving plane of laser illumination beam 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 2V2 and 2V3, the PLIIM system of Fig. 2V1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and a 1-D image detection array 3 (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view sweeping mirror 9 operably connected to a motor mechanism 38 under control of system controller 22, for folding and sweeping the field of view of the image formation and detection module 3; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding/sweeping mirrors 37A and 37B operably connected to motor mechanisms 39A and 39B, respectively, under control of system controller 22, for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9; an image frame grabber 19 operably connected to the

linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

An image formation and detection (IFD) module 3 having an imaging lens with a fixed focal length has a constant angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's FOV become on the surface of the target object. A disadvantage to this type of imaging lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, varies as a function of the distance from the target object to the imaging lens. However, a fixed focal length imaging lens is easier and less expensive to design and produce than the alternative, a zoom-type imaging lens which will be discussed in detail hereinbelow with reference to Figs. 3A through 3J4.

Each planar laser illumination module 6A through 6B in PLIIM system 1' is driven by a VLD driver circuit 18 under the system controller 22. Notably, laser illumination beam folding/sweeping mirror 37A' and 38B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 38. 39A, and 39B, respectively, operated under the control of the system controller 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which is synchronously controlled to enable the planar laser illumination beams 7A. 7B and FOV 10 to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B. the linear image formation and detection module 3, the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3 and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A' and 6B' , beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3 and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 1' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

<u>Applications For The Second Generalized Embodiment Of The PLIIM System Of The Present Invention</u>

The fixed focal length PLIIM system shown in Figs. 1V1-1V3 has a 3-D fixed field of view which, while spatially-aligned with a composite planar laser illumination beam 12 in a coplanar manner, is automatically swept over a 3-D scanning region within which bar code symbols and other graphical indicia 4 may be illuminated and imaged in accordance with the principles of the present invention. As such, this generalized embodiment of the present invention is ideally suited for use in hand-supportable and hands-free presentation type bar code symbol readers shown in Figs. 1V4 and 1V5, respectively, in which rasterlike-scanning (i.e. up and down) patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIM system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicant's copending US Application Nos. 09/204,176 entitled filed December 3, 1998 and 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000, incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

<u>Third Generalized Embodiment Of The PLIIM System Of The Present Invention</u>

The third generalized embodiment of the PLIIM system of the present invention 40 is illustrated in Fig. 2A. As shown therein. the PLIIM system 40 comprises: a housing 2 of compact construction: a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3' including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B' having a fixed focal length, a variable focal distance. and a fixed field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing: and a pair of planar laser illumination arrays (PLIAs) 6A and 6B , each mounted on opposite sides of the IFD module 3', such that each planar laser illumination array 6A and 6B produces a composite plane of laser beam illumination 12 which is disposed substantially coplanar with the field view of the image formation and detection module 3' during object illumination and image detection operations carried out by the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', and any non-moving FOV and/or planar laser illumination beam folding mirrors employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and any

stationary FOV folding mirrors employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and any planar laser illumination beam folding mirrors employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 40 employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

An image formation and detection (IFD) module 3 having an imaging lens with variable focal distance, as employed in the PLIIM system of Fig. 2A, can adjust its image distance to compensate for a change in the target's object distance: thus, at least some of the component lens elements in the imaging subsystem are movable, and the depth of field of the imaging subsystems does not limit the ability of the imaging subsystem to accommodate possible object distances and orientations. A variable focus imaging subsystem is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good focus no matter where the target object might be located. Variable focus can be accomplished in several ways, namely: by moving lens elements; moving imager detector/sensor; and dynamic focus. Each of these different methods will be summarized below for sake of convenience.

Use Of Moving Lens Elements In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can employ an imaging lens which is made up of several component lenses contained in a common lens barrel. A variable focus type imaging lens such as this can move one or more of its lens elements in order to change the effective distance between the lens and the image sensor, which remains stationary. This change in the image distance compensates for a change in the object distance of the target object and keeps the return light in focus. The position at which the focusing lens element(s) must be in order to image light returning from a target object at a given object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the optics art.

Use Of An Moving Image Detection Array In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can be constructed so that all the lens elements remain stationary, with the imaging detector/sensor array being movable relative to the imaging lens so as to change the image distance of the imaging subsystem. The position at which the image detector/sensor must be located to image light returning from a target at a given object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the art.

Use Of Dynamic Focal Distance Control In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can be designed to embody a "dynamic" form of variable focal distance (i.e. focus) control, which is an advanced form of variable focus control. In conventional variable focus control schemes, one focus (i.e. focal distance) setting is established in anticipation of a given target object. The object is imaged using that setting, then another setting is selected for the next object image, if necessary. However, depending on the shape and orientation of the target object, a single target object may exhibit enough variation in its distance from the imaging lens to make it impossible for a single focus setting to acquire a sharp image of the entire object. In this case, the imaging subsystem must change its focus setting while the object is being imaged. This adjustment does not have to be made continuously; rather, a few discrete focus settings will generally be sufficient. The exact number will depend on the shape and orientation of the package being imaged and the depth of field of the imaging subsystem used in the IFD module.

It should be noted that dynamic focus control is only used with a linear image detection/sensor array, as used in the system embodiments shown in Figs. 2A through 3J4. The reason for this limitation is quite clear: an area-type image detection array captures an entire image after a rapid number of exposures to the planar laser illumination beam, and although changing the focus setting of the imaging subsystem might clear up the image in one part of the detector array, it would induce blurring in another region of the image, thus failing to improve the overall quality of the acquired image.

First Illustrative Embodiment Of The PLIIM System Shown In Fig. 2A

The first illustrative embodiment of the PLIIM system of Fig. 2A 40A is shown in Fig. 2B1. As illustrated therein, the field of view of the image formation and detection module 3' and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM system illustrated in Fig. 2B1 is shown in greater detail in Fig. 2B2. As shown therein, the linear image formation and detection module 3' is shown comprising an imaging subsystem 3B', and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images (e.g. 6000 pixels, @ 60MHZ scanning rate) formed thereon by the imaging subsystem 3B', providing an image resolution of 200dpi or 8 pixels/mm, as the image resolution that results from a fixed focal length imaging lens is the function of the object distance (i.e. the longer the object distance, the lower the resolution). The imaging subsystem 3B' has a fixed focal length imaging lens (e.g. 80mm Pentax lens, F4.5), a fixed field of view (FOV), and a variable focal distance imaging capability (e.g. 36" total scanning range), and an auto-focusing image plane with a response time of about 20-30 milliseconds over about 5mm working range.

As shown, each planar laser illumination array (PLIA) 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each

other, in a rectilinear fashion. As taught hereinabove, the relative spacing and orientation of each PLIM 11 is such that the spatial intensity distribution of the individual planar laser beams 7A, 7B superimpose and additively produce composite planar laser illumination beam 12 having a substantially uniform power density distribution along the widthwise dimensions of the laser illumination beam, throughout the entire working range of the PLIIM system.

As shown in Fig. 2C1, the PLIIM system of Fig. 2B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2C2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2B1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 30 contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3B' mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with an optical element translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements back and forth with translator 3C in response to a first set of control signals 3E generated by the system controller, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the system controller 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A

The second illustrative embodiment of the PLIIM system of Fig. 2A 40B is shown in Fig. 2D1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a

linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3' such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12 produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

One primary advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3' can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 2D2, the PLIIM system of Fig. 2D1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18: linear-type image formation and detection module 3': a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3', for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2D2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2D1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A' mounted along the optical bench before the image detecting array 3A', and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with a translator 3E in response to a first set of control signals 3E generated by the system controller 22, while the entire group of focal

lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the system controller. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Third Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A

The second illustrative embodiment of the PLIIM system of Fig. 2A 40C is shown in Fig. 2D1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B, and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the field of view of the image formation and detection during object illumination and image detection operations.

The primary disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light and therefore the return laser light slightly. Also this embodiment requires a complicated beam/FOV adjustment scheme. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench 8 as far back as possible from the beam folding mirrors 37A, 37B, and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11.

As shown in Fig. 2E2, the PLIIM system of Fig. 2E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images

stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2E3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2E1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3Amounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the system controller 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the system controller 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A

The fourth illustrative embodiment of the PLIIM system of Fig. 2A 40D is shown in Fig. 2F1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the FOV of the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam folding mirrors 37A and 37B arranged in relation to the planar laser illumination arrays 6A and 6B so as to fold the optical paths of the first and second planar laser illumination beams 7A, 7B in a direction that is coplanar with the folded FOV of the image formation and detection module 3', during object illumination and image detection operations.

As shown in Fig. 2F2, the PLIIM system 40D of Fig. 2F1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19

operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2F3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2F1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench 3D before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the system controller 22. Regardless of the approach taken, an IFD module with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Third Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM systems shown in Figs. 2A through 2F3 employ an IFD module 3' having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM systems are good candidates for use in a conveyor top scanner application, as shown in Figs. 2G, as the variation in target object distance can be up to a meter or more (from the imaging subsystem). In general, such object distances are too great a range for the depth of field (DOF) characteristics of the imaging subsystem alone to accommodate such object distance parameter variations during object illumination and imaging operations. Provision for variable focal distance control is generally sufficient for the conveyor top scanner application shown in Fig. 2G, as the demands on the depth of field and variable focus or dynamic focus control characteristics of such PLIIM system are not as severe in the conveyor top scanner

application, as they might be in the conveyor side scanner application, also illustrated in Fig. 2G.

Notably, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 2A through 2F3, the resulting PLIIM system becomes appropriate for the conveyor side-scanning application discussed above, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

Fourth Generalized Embodiment Of The PLIIM System Of The Present Invention

The fourth generalized embodiment of the PLIIM system 40' of the present invention is illustrated in Figs. 2I1 and 2I2. As shown in Fig. 2I1, the PLIIM system 40' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a moving planar laser illumination beam 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 2I2 and 2I3, the PLIIM system of Fig. 2I1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera. from Dalsa. Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view 10 of the image formation and detection module 3'; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B. respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. As shown in Fig. 2F2, each planar laser illumination module 11A through 11F, is driven by a VLD driver circuit 18 under the system controller 22. Notably, laser illumination beam folding/sweeping mirrors 37A' and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B.

38, respectively, operated under the control of the system controller 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the composite planar laser illumination beam and FOV to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM system.

Fig. 2I4 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2I1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the system controller 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with a translator 3C in response to a first set of control signals 3E generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the system controller 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B, beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3' and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 40' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Fourth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 2I1 through 2I4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, and (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in an "up and down" pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" hereindisclosed, such PLIIM systems are good candidates for use in a hand-held scanner application, shown in Figs. 2I5, and the hands-free presentation scanner application illustrated in Fig. 2I6. The provision of variable focal distance control in these illustrative PLIIM systems is most sufficient for the hand-held scanner application shown in Fig. 2I5, and presentation scanner application shown in Figs. 2I6, as the demands placed on the depth of field and variable focus control characteristics of such systems will not be severe.

Fifth Generalized Embodiment Of The PLIIM System Of The Present Invention

The fifth generalized embodiment of the PLIIM system of the present invention 50 is illustrated in Fig. 3A. As shown therein, the PLIIM system 50 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3" including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B" having a variable focal length, a variable focal distance, and a variable field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 3", such that each planar laser illumination array 6A and 6B produces a plane of laser beam illumination 7A, 7B which is disposed substantially coplanar with the field view of the image formation and detection module 3" during object illumination and image detection operations carried out by the PLIIM system.

In the PLIIM system of Fig. 3A, the linear image formation and detection (IFD) module 3" has an imaging lens with a variable focal length (i.e. a zoom-type imaging lens) 3B1, that has a variable angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's FOV become on the surface of the target object. A zoom imaging lens is capable of changing its focal length, and therefore its angular field of view (FOV) by moving one or more of its component lens elements. The position at which the zooming lens element(s) must be in order to achieve a given focal length is determined by consulting a lookup table, which must be constructed ahead of time either experimentally or by design software, in a manner well known in the art. An advantage to using a zoom lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, remains constant no matter what the distance from the target object to the lens.

However, a zoom camera lens is more difficult and more expensive to design and produce than the alternative, a fixed focal length camera lens.

The image formation and detection (IFD) module 3" in the PLIIM system of Fig. 3A also has an imaging lens 3B2 with variable focal distance, which can adjust its image distance to compensate for a change in the target's object distance. Thus, at least some of the component lens elements in the imaging subsystem 3B2 are movable, and the depth of field (DOF) of the imaging subsystem does not limit the ability of the imaging subsystem to accommodate possible object distances and orientations. This variable focus imaging subsystem 3B2 is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good image focus no matter where the target object might be located. This variable focus technique can be practiced in several different ways, namely: by moving lens elements in the imaging subsystem; by moving the image detection/sensing array relative to the imaging lens; and by dynamic focus control. Each of these different methods has been described in detail above.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B the image formation and detection module 3" are fixedly mounted on an optical bench or chassis assembly 8 so as to prevent any relative motion between (i) the image forming optics (e.g. camera lens) within the image formation and detection module 3" and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) employed in the PLIIM system which might be caused by vibration or temperature changes. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3", as well as be easy to manufacture, service and repair. Also, this PLIIM system employs the general "planar laser illumination" and "FBAFOD" principles described above.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3B1

The first illustrative embodiment of the PLIIM system of Fig. 3A 50A is shown in Fig. 3B1. As illustrated therein, the field of view of the image formation and detection module 3" and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM system 50A illustrated in Fig. 3B1 is shown in greater detail in Fig. 3B2. As shown therein, the linear image formation and detection module 3" is shown comprising an imaging subsystem 3B", and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B". The imaging subsystem 3B" has a variable focal length imaging lens, a variable focal distance and a variable field of view. As shown, each planar laser illumination array 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. As taught

hereinabove, the relative spacing of each PLIM 11 is such that the spatial intensity distribution of the individual planar laser beams superimpose and additively provide a composite planar case illumination beam having substantially uniform composite spatial intensity distribution for the entire planar laser illumination array 6A and 6B.

As shown in Fig. 3C1, the PLIIM system 50A of Fig. 3B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3C2 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3B1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1 , functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C1 in response to a first set of control signals generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C1 in response to a first set of control signals 3E2 generated by the system controller 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B2 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E2 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

A preferred implementation of the image subsystem of Fig. 3C2 is shown in Fig. 3D. As shown in Fig. 3D, imaging subsystem 3B" comprises: an optical bench 3D having a pair of rails, along which mounted optical elements are translated; a linear CCD-type image detection array 3A (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa,

Inc. USA—http:/www/dalsa.com) fixedly mounted to one end of the optical bench; a system of stationary lenses 3A1 fixedly mounted before the CCD-type linear image detection array 3A; a first system of movable lenses 3B1 slidably mounted to the rails of the optical bench 3D by a set of ball bearings, and designed for stepped movement relative to the stationary lens subsystem 3A1 with translator 3C1 in automatic response to a first set of control signals 3E1 generated by the system controller 22; and a second system of movable lenses 3B2 slidably mounted to the rails of the optical bench by way of a second set of ball bearings, and designed for stepped movements relative to the first system of movable lenses 3B with translator 3C2 in automatic response to a second set of control signals 3D2 generated by the system controller 22. As shown in Fig. 3D, a large stepper wheel 42 driven by a zoom stepper motor 43 engages a portion of the zoom lens system 3B1 to move the same along the optical axis of the stationary lens system 3A1 in response to control signals 3C1 generated from the system controller 22. Similarly, a small stepper wheel 44 driven by a focus stepper motor 45 engages a portion of the focus lens system 3B2 to move the same along the optical axis of the stationary lens system 3A1 in response to control signals 3E2 generated from the system controller 22.

Method of Adjusting the Focal Characteristics of the Planar Laser Illumination Beams Generated by Planar Laser Illumination Arrays Used in Conjunction with Image Formation And Detection Modules Employing Variable Focal Length (Zoom) Imaging Lenses

Unlike the fixed focal length imaging lens case, there occurs a significant a $1/r^2$ drop-off in laser return light intensity at the image detection array when using a zoom (variable focal length) imaging lens in the PLIIM system hereof. In PLIIM system employing an imaging subsystem having a variable focal length imaging lens, the area of the imaging subsystem's field of view (FOV) remains constant as the working distance increases. Such variable focal length control is used to ensure that each image formed and detected by the image formation and detection (IFD) module 3" has the same number of "dots per inch" (DPI) resolution. regardless of the distance of the target object from the IFD module 3". However, since module's field of view does not increase in size with the object distance, equation (8) must be rewritten as the equation (10) set forth below

$$E_{ccd}^{zoom} = \frac{E_0 f^2 s^2}{8d^2 F^2 r^2}$$
(10)

where s^2 is the area of the field of view and d^2 is the area of a pixel on the image detecting array. This expression is a strong function of the object distance, and demonstrates $1/r^2$ drop off of the return light. If a zoom lens is to be used, then it is desirable to have a greater power density at the farthest object distance than at the nearest, to compensate for this loss. Again, focusing the beam at the farthest object distance is the technique that will produce this result.

Therefore, in summary, where a variable focal length (i.e. zoom) imaging subsystem is employed in the PLIIM system, the planar laser beam focusing technique of the present invention described above helps compensate for (i) decreases in the power density of the incident illumination beam due to the fact that the width of the planar laser illumination beam increases

for increasing distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser planar illumination beam of the present invention.

<u>Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A</u>

The second illustrative embodiment of the PLIIM system of Fig. 3A 50B is shown in Fig. 3E1 comprising: an image formation and detection module 3" having an imaging subsystem 3B with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3"; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3" such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12 produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

As shown in Fig. 3E2, the PLIIM system of Fig. 3E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A; a field of view folding mirror 9' for folding the field of view of the image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3E3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3E1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of

stationary focal lens elements 3B2. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C2 in response to a first set of control signals 3E2 generated by the system controller 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module 3" with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Detailed Description Of An Exemplary Realization Of The PLIIM System Shown In Fig. 3E1 through 3E3

Referring now to Figs. 3E4 through 3E8, an exemplary realization of the PLIIM system 50B shown in Figs. 3E1 through 3E3 will now be described in detail below.

As shown in Figs. 3E41 and 3E5, an exemplary realization of the PLIIM system 50B Figs. 3E1-3E3 is indicated by reference numeral 25' contained within a compact housing 2 having height, length and width dimensions of about 4.5", 21.7" and 19.7", respectively, to enable easy mounting above a conveyor belt structure or the like. As shown in Fig. 3E4, 3E5 and 3E6, the PLIIM system comprises a linear image formation and detection module 3", a pair of planar laser illumination arrays 6A, and 6B, and a field of view (FOV) folding structure (e.g. mirror, refractive element, or diffractive element) 9. The function of the FOV folding mirror 9 is to fold the field of view (FOV) 10 of the image formation and detection module 3' in an imaging direction that is coplanar with the plane of laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B. As shown, these components are fixedly mounted to an optical bench 8 supported within the compact housing 2 so that these optical components are forced to oscillate together. The linear CCD imaging array 3A can be realized using a variety of commercially available high-speed line-scan camera systems such as, for example, the Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com. Notably, image frame grabber 19, image data buffer (e.g. VRAM) 20, decode image processor 21, and system controller 22 are realized on one or more printed circuit (PC) boards contained within a camera and system electronic module 27 also mounted on the optical bench, or elsewhere in the system housing 2.

While this system design requires additional optical surfaces (i.e. planar laser beam folding mirrors) which complicates laser-beam/FOV alignment, and attenuates slightly the intensity of collected laser return light, this system design will be beneficial when the FOV of the imaging subsystem cannot have a large apex angle, as defined as the angular aperture of the imaging lens (in the zoom lens assembly), due to the fact that the IFD module 3" must be

mounted on the optical bench in a backed-off manner to the conveyor belt (or maximum object distance plane), and a longer focal length lens (or zoom lens with a range of longer focal lengths) is chosen.

One notable advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3" can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 3E4, the compact housing 2 has a relatively long light transmission window 28 of elongated dimensions for the projecting the FOV 10 of the image formation and detection module 3" through the housing towards a predefined region of space outside thereof, within which objects can be illuminated and imaged by the system components on the optical bench. Also, the compact housing 2 has a pair of relatively short light transmission apertures 30A and 30B, closely disposed on opposite ends of light transmission window 28, with minimal spacing therebetween, as shown in Fig. 3E4. Such spacing is to ensure that the FOV emerging from the housing 2 can spatially overlap in a coplanar manner with the substantially planar laser illumination beams projected through transmission windows 29A and 29B, as close to transmission window 28 as desired by the system designer, as shown in Figs. 3E6 and 3E7. Notably, in some applications, it is desired for such coplanar overlap between the FOV and planar laser illumination beams to occur very close to the light transmission windows 28, 29A and 29B (i.e. at short optical throw distances). but in other applications, for such coplanar overlap to occur at large optical throw distances.

In either event, each planar laser illumination array 6A and 6B is optically isolated from the FOV of the image formation and detection module 3" to increase the signal-to-noise ratio (SNR) of the system. In the preferred embodiment, such optical isolation is achieved by providing a set of opaque wall structures 30A, 30B about each planar laser illumination array, extending from the optical bench 8 to its light transmission window 29A or 29B, respectively. Such optical isolation structures prevent the image formation and detection module 3" from detecting any laser light transmitted directly from the planar laser illumination arrays 6A and 6B within the interior of the housing. Instead, the image formation and detection module 3" can only receive planar laser illumination that has been reflected off an illuminated object, and focused through the imaging subsystem 3B" of the IFD module 3".

Notably, the linear image formation and detection module of the PLIIM system of Fig. 3E4 has an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance, and a variable field of view. In Fig. 3E8, the spatial limits for the FOV of the image formation and detection module are shown for two different scanning conditions, namely: when imaging the tallest package moving on a conveyor belt structure; and when imaging objects having height values close to the surface of the conveyor belt structure. In a PLIIM system

having a variable focal length imaging lens and a variable focusing mechanism, the PLIIM system would be capable of imaging at either of the two conditions indicated above.

Third Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A

The third illustrative embodiment of the PLIIM system of Fig. 3A 50C is shown in Fig. 3F1 comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view; and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B, respectively; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module 3" during object illumination and imaging operations.

One notable disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light and therefore the return laser light slightly. Also this system design requires a more complicated beam/FOV adjustment scheme than the direct-viewing design shown in Fig. 3B1. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors 37A and 37B. and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11A through 11P.

As shown in Fig. 3F2, the PLIIM system of Fig. 3F1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F. and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A;; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and 7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3F3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3F1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A' mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2 , functioning as a focal lens assembly, movably mounted along the optical bench 3D in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the system controller, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator in response to a first set of control signals 3E2 generated by the system controller 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A

The fourth illustrative embodiment of the PLIIM system of Fig. 3A 50D is shown in Fig. 3G1 comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a FOV folding mirror 9 for folding the FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module during object illumination and image detection operations.

As shown in Fig. 3G2, the PLIIM system of Fig. 3G1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3"; a FOV folding mirror 9 for folding the

FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer 20; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3G3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3G1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the system controller 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E2 generated by the system controller 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3C1 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Fifth Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM systems shown in Figs. 3A through 3G3 employ an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focus (i.e. focal distance) control mechanisms, such PLIIM systems are good candidates for use in the conveyor top scanner application shown in Fig. 3H, as variations in target object distance can be up to a meter or more (from the imaging subsystem) and the imaging subsystem provided therein can easily accommodate such object distance parameter variations during object

illumination and imaging operations. Also, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 3A through 3F3, the resulting PLIIM system will become appropriate for the conveyor side scanning application also shown in Fig. 3G, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

Sixth Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging System Of The Present Invention

The sixth generalized embodiment of the PLIIM system of Fig. 3A 50' is illustrated in Figs. 3J1 and 3J2. As shown in Fig. 3J1, the PLIIM system 50' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3"; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3". During system operation, laser illumination arrays 6A and 6B each produce a composite laser illumination beam 12 which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3", so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 2-D scanning region.

As shown in Figs. 3J2 and 3J3, the PLIIM system of Fig. 3J1 50' comprises: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http:/www/dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view of the image formation and detection module 3"; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding and sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 3J3, each planar laser illumination module 11A through 11F is driven by a VLD driver circuit 18 under the system controller 22 in a manner well known in the art. Notably, laser illumination beam folding/sweeping mirror 37A' and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B, and 38, respectively, operated under the control of the system controller 22. These three mirror

elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the planar laser illumination beams and FOV to move together during illumination and detection operations within the PLIIM system.

Fig. 3J4 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3J1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3B" mounted stationary relative to the image detecting array 3A1 a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the system controller, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C2 in response to a first set of control signals 3E1 generated by the system controller 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3", the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3" and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B, beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3" and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Sixth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 3J1 through 3J4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance control mechanisms, and also (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in a raster-like pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" herein disclosed, such PLIIM systems are good candidates for use in a hand-held scanner application, shown in Fig. 3J5, and the hands-free presentation scanner application illustrated in Fig. 3J6. As such, these embodiments of the present invention are ideally suited for use in hand-supportable and presentation-type hold-under bar code symbol reading applications shown in Figs. 3J5 and 3J6, respectively, in which raster--like ("up and down") scanning patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIM system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicant's copending US Application No. 09/204,17+ filed December 3, 1998, U.S. Application No. 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000 incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

Seventh Generalized Embodiment Of The PLIIM System Of The Present Invention

The seventh generalized embodiment of the PLIIM system of the present invention 60 is illustrated in Fig. 4A. As shown therein. the PLIIM system 60 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55 including a 2-D electronic image detection array 55A, and an area (2-D) imaging subsystem (LIS) 55B having a fixed focal length, a fixed focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55, for producing first and second planes of laser beam illumination 7A and 7B that are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module 55 during object illumination and image detection operations carried out by the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55, and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on

an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55 and any stationary FOV folding mirror employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55, as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 4A

The first illustrative embodiment of the PLIIM system of Fig. 4A 60A is shown in Fig. 4B1 comprising: an image formation and detection module (i.e. camera) 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view (FOV) of three-dimensional extent, and an area (2-D) array of photo-electronic detectors 55A realized using high-speed CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D area images formed thereon by the imaging subsystem 55B; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the 3-D FOV 40' of image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 4B2, the PLIIM system 60A of Fig. 4B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 4A

The second illustrative embodiment of the PLIIM system of Fig. 4A 601 is shown in Fig. 4C1 comprising: an image formation and detection module 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

In general, the area image detection array 55B employed in the PLIEM systems shown in Figs. 4A through 6F4 has multiple rows and columns of pixels arranged in a rectangular array. Therefore, area image detection array is capable of sensing/detecting a complete 2-D image of a target object in a single exposure, and the target object may be stationary with respect to the PLIIM system. Thus, the image detection array 55D is ideally suited for use in hold-under type scanning systems However, the fact that the entire image is captured in a single exposure implies that the technique of dynamic focus cannot be used with an area image detector.

As shown in Fig. 4C2, the PLIIM system of Fig. 4C1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B. and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55B; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof, including synchronous driving motors 58A and 68B, in an orchestrated manner.

Applications For The Seventh Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

The fixed focal distance area-type PLIIM systems shown in Figs. 4A through 4C2 are ideal for applications in which there is little variation in the object distance, such as in a 2-D hold-under scanner application as shown in Fig. 4D. A fixed focal distance PLIIM system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM systems are good choices for the hands-free presentation and hand-held scanners applications illustrated in Figs. 4D and 4E, respectively, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to twelve or more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length imaging lens, the variation in object distance implies that the dpi resolution of acquired images will vary as well, and therefore image-based bar code symbol decode-processing techniques must address such variations in image resolution. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM system.

Eighth Generalized Embodiment Of The PLIIM System Of The Present Invention

The eighth generalized embodiment of the PLIIM system of the present invention 70 is illustrated in Fig. 5A. As shown therein, the PLIIM system 70 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B' having a fixed focal length, a variable focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A. so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55'. for producing first and second planes of laser beam illumination 7A and 7B such that the 3-D field of view 10' of the image formation and detection module 55' is disposed substantially coplanar with the planes of the first and second planar laser illumination beams 7A, 7B during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig. 5D, wherein a person picks up a package, holds it under the scanning system to allow the bar

code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55', and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55' and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) 55' and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly 8 should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Shown In Fig. 5A

The first illustrative embodiment of the PLIIM system of Fig. 5A, indicated by reference numeral 70A, is shown in Figs. 5B1 and 5B2 comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view (of 3-D spatial extent), and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams 7A, 7B are disposed substantially coplanar with a section of the 3-D FOV (10') of the image formation and detection module 55' during object illumination and imaging operations carried out by the PLIIM system.

Planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55'; planar laser illumination beam folding/sweeping mirrors 57A and 57B, driven by motors 58A and 58B, respectively; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received

from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. The operation of this system configuration is as follows. Images detected by the low-resolution area camera 61 are grabbed by the image frame grabber 62 and provided to the decode image processor 21 by the system controller 22. The decode image processor 21 automatically identifies and detects when a label containing a bar code symbol structure has moved into the 3-D scanning field, whereupon the high-resolution CCD detection array camera 55A is automatically triggered by the system controller 22. At this point, the planar laser illumination beams 12' begin to sweep the 3-D scanning region, images are captured by the high-resolution array 55A and the decode image processor 21 decodes the detected bar code by a more robust bar code symbol decode software program.

Fig. 5B4 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM system of Fig. 5B3. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1' mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1'. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the system controller 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2' back and forth with translator 55C in response to a first set of control signals 55E generated by the system controller, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2' to be moved in response to control signals generated by the system controller 22. Regardless of the approach taken, an IFD module 55' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 5A

The second illustrative embodiment of the PLIIM system of Fig. 5A is shown in Figs. 5C1, 5C2 comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels

for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module 55' during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 5C2, the PLIIM system of Fig. 5C1 comprises: As shown in Fig. 5C3, the PLIIM system 70A of Fig. 5C1 is shown in slightly greater detail comprising: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55'; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B, driven by motors 58A and 58B, respectively; an image frame grabber 19 operably connected to area-type image formation and detection module 55', for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 5C3 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM system of Fig. 5C1. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1 mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2 (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the system controller 22, while the

entire group of focal lens elements 55B1 remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2 back and forth with the translator 55C in response to a first set of control signals 55E generated by the system controller, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2 to be moved in response to control signals generated by the system controller. Regardless of the approach taken, the IFD module 55B' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Eighth Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM systems shown in Figs. 5A through 5C4 employ an IFD module having an area image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM systems are good candidates for use in a presentation scanner application. as shown in Fig. 5D, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM system will be sufficient to accommodate for expected target object distance variations.

Ninth Generalized Embodiment Of The PLIIM System Of The Present Invention

The ninth generalized embodiment of the PLIIM system of the present invention 80 is illustrated in Fig. 6A. As shown therein, the PLIIM system 80 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B" having a variable focal length, a variable focal distance. and a variable field of view (FOV) of 3-D spatial extent, for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55", for producing first and second planes of laser beam illumination 7A and 7B such that the field of view of the image formation and detection module 55" is disposed substantially coplanar with the planes of the first and second planar laser illumination beams during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig. 5D, wherein a person picks up a package, holds it under the scanning system to allow the

bar code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55", and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 6A

The first illustrative embodiment of the PLIIM system of Fig. 6A indicated by reference numeral 8A is shown in Figs. 6B1 and 6B2 comprising: an area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55A; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 6B3, the PLIIM system of Fig. 6B1 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so);planar laser

illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55B; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6B4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM system of Fig. 6B31. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55B1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and forth with translator 55C1 in response to a first set of control signals generated by the system controller, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis in response to a first set of control signals 55E2 generated by the system controller 22, while the second group of focal lens elements 55B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator 55C2 in response to a second set of control signals 55E2 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 6A

The second illustrative embodiment of the PLIIM system of Fig. 6A is shown in Fig. 6C1 and 6C2 comprising: an image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D) array of photo-electronic detectors 55A realized using

CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55B"; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 6C2, the PLIIM system of Figs. 6C1 and 6C2 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55A; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55" for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6C4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM system of Fig. 6C1. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55A1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and

forth with translator 55C1 in response to a first set of control signals 55E1 generated by the system controller 22, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C1 in response to a first set of control signals 55A generated by the system controller 22, while the second group of focal lens elements 55B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator in response to a second set of control signals 55E2 generated by the system controller 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Ninth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 6A through 6C4 employ an IFD module having an area-type image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance (focus) control mechanism, such PLIIM systems are good candidates for use in a presentation scanner application, as shown in Fig. 6D, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM system will be sufficient to accommodate for expected target object distance variations. All digital images acquired by this PLIIM system will have substantially the same dpi image resolution. regardless of the object's distance during illumination and imaging operations. This feature is useful in 1-D and 2-D bar code symbol reading applications.

Tenth Generalized Embodiment Of The PLIIM System Of The Present Invention. Wherein A 3-D Field Of View And A Pair Of Planar Laser Illumination Beams Are Controllably Steered About A 3-D Scanning Region

Referring to Figs. 6E1 through 6E4, the tenth generalized embodiment of the PLIIM system of the present invention 90 will now be described, wherein a 3-D field of view 101 and a pair of planar laser illumination beams are controllably steered about a 3-D scanning region in order to achieve a greater region of scan coverage.

As shown in Fig. 6E2, PLIIM system of Fig. 6E1 comprises: an area-type image formation and detection module 55'; a pair of planar laser illumination arrays 6A and 6B; a pair of x and y axis field of view (FOV) sweeping mirrors 91A and 91B, driven by motors 92A and 92B, respectively, and arranged in relation to the image formation and detection module 55"; a pair of x and y axis planar laser illumination beam folding and sweeping mirrors 93A and 93B, driven by motors 94 and 94B, respectively, and a pair of x and y planar laser illumination beam folding and sweeping mirrors 95A and 95B, driven by motors 96A and 96B, respectively, and wherein mirrors, 93A, 93B and 95A, 95B are arranged in relation to the pair of planar laser beam illumination beam arrays 65 and 66, respectively, such that the planes of the laser illumination

beams 7A, 7B are coplanar with a planar section of the 3-D field of view (101) of the image formation and detection module 55" as the planar laser illumination beams and the FOV of the IFD module 55" are synchronously scanned across a 3-D region of space during object illumination and image detection operations.

As shown in Fig. 6E3, the PLIIM system of Fig. 6E2 comprises: area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view (FOV) of 3-D spatial extent. and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL.Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55A; planar laser illumination arrays, 6A, 6B; x and y axis FOV steering mirrors 91A and 91B; x and y axis planar laser illumination beam sweeping mirrors 93A and 93B, and 95A and 95B; an image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Area-type image formation and detection module 55" can be realized using a variety of commercially available high-speed area-type CCD camera systems such as, for example, the KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor, from Eastman Kodak Company-Microelectronics Technology Division—Rochester. New York.

Fig. 6F4 illustrates a portion of the system 90 in Fig. 6E1, wherein the 3-D field of view (FOV) of the image formation and detection module 55" is shown steered over the 3-D scanning region of the system using a pair of x and y axis FOV folding mirrors 91A and 91B, which work in cooperation with the x and y axis planar laser illumination beam folding/steering mirrors 93A and 93B and 95A and 95B to steer the pair of planar laser illumination beams 7A and 7B in a coplanar relationship with the 3-D FOV (101), in accordance with the principles of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55", folding/sweeping FOV folding mirrors 91A and 91B, and planar laser beam illumination folding/sweeping mirrors 93A, 93B, 95A and 95B employed in this system embodiment, are mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and FOV folding/sweeping mirrors 91A, 91B employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror 93A, 93B, 95A and 95B employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure

alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The Hybrid Holographic/CCD-Based PLIIM System Of The Present Invention

In Fig. 7A, a first illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention 100 is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using a linear image detection array having a 2-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM system will be supported over a conveyor belt structure which transports packages past the PLIIM system 100 at a substantially constant velocity so that lines of scan data can be combined together to construct 2-D images upon which decode image processing algorithms can be performed.

As illustrated in Fig. 7A, the hybrid holographic/CCD-based PLIIM system 100 comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams 7A and 7B that produce a composite planar laser illumination beam 12 for illuminating a target object residing within a 3-D scanning volume; a holographic-type cylindrical lens 101 is used to collimate the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type volume holographic optical elements (HOE) 103, as taught in U.S. Patent No. 5,984,185, incorporated herein by reference. Each HOE 103 on the imaging disc 102 has a different focal length, which is disposed before a linear (1-D) CCD image detection array 3A. The holographic imaging disc 102 and image detection array 3A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 7A, the PLIIM system 100 further comprises: an image frame grabber 19 operably connected to linear-type image formation and detection module 3A, for accessing 1-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 7B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays 6A and 6B, and the variable field of

view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. The advantage of this hybrid system design is that it enables the generation of a 3-D image-based scanning volume having multiple depths of focus by virtue of the holographic-based variable focal length imaging subsystem employed in the PLIIM system.

Second Illustrative Embodiment Of The Hybrid Holographic/CCD-Based PLIIM System Of The Present Invention

In Fig. 8A, a second illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention 100' is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using an area-type image detection array having a 3-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM system 100' can used in a holder-over type scanning application, hand-held scanner application, or presentation-type scanner.

As illustrated in Fig. 8A, the hybrid holographic/CCD-based PLIIM system 101' comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding/sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams through the 3-D field of view of the imaging subsystem; a holographic-type cylindrical lens 101 for collimating the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type volume holographic optical elements (HOE) 103, as the disc is rotated about its rotational axis. Each HOE 103 on the imaging disc has a different focal length, and is disposed before an area (2-D) type CCD image detection array 55A. The holographic imaging disc 102 and image detection array 55A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object (i.e. working) distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 8A, the PLIIM system 101' further comprises: an image frame grabber 19 operably connected to an area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; a decode image processor 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a system controller 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 8B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays 6A and 6B, and the variable field of view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. The advantage of this hybrid system design is that it enables the generation of

a 3-D image-based scanning volume having multiple depths of focus by virtue of the holographic-based variable focal length imaging subsystem employed in the PLIIM system.

First Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem

Referring now to Figs. 9 and 10, a unitary package identification and dimensioning system of the first illustrated embodiment 120 will now be described in detail.

As shown in Fig. 10, the unitary system 120 of the present invention comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 121, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 121 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 10, the unitary system comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacing as taught in copending US Application No. 09/327,756 filed June 7, 1999, supra; and International PCT Application No. PCT/US00/15624 filed December 7, 2000, incorporated herein by reference; (2) a PLIIM-based bar code symbol reading subsystem 25' for producing a 3-D scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and output from the unitary system; and (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions.

As shown in Fig. 10, the package imaging, detecting and dimensioning subsystem 122 comprises a number of subsystems integrated therewithin as shown, namely: a package velocity measurement subsystem 123, for measuring the velocity of transported packages by analyzing range data maps generated by the different scanning beams, using the inventive methods disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000; a package-in-the-tunnel (PITT) indication subsystem 125, for automatically detecting the presence of each package moving through the scanning volume by reflecting a portion of one of the laser scanning beams across the width of the conveyor belt in a retro-reflective manner and then analyzing the return signal using first derivative and thresholding techniques disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000; a package (x-y) height/width/length dimensioning (or profiling) subsystem 124, integrated within subsystem 122, for producing x,y,z profile data sets for detected packages; and a package-out-of-the-tunnel (POOT) indication subsystem 125, integrated within subsystem 122, realized using predictive techniques based on the output of the PITT indication subsystem 125, for automatically detecting the presence of packages moving out of the scanning volume. As shown in Fig. 10, the unitary system 120 is adapted to receive data inputs from a number of input devices including, for example: weighing-in-motion subsystem 132 for weighing packages as they are transported

along the conveyor belt; an RF-tag reading subsystem for reading RF tags on packages as they are transported along the conveyor belt; etc.

The primary function of subsystem 122 is to measure dimensional characteristics of packages passing through the scanning volume, and produce package dimension data for each dimensioned package. The primary function of scanning subsystem 25' is to read bar code symbols on dimensioned packages and produce package identification data representative of each identified package. The primary function of the I/O subsystem 127 is to transport package dimension data elements and package identification data elements to the data element queuing, handling and processing subsystem 131. The primary function of the data element queuing, handling and processing subsystem 131 is to link each package dimension data element with its corresponding package identification data element, and to transport such data element pairs to an appropriate host system for subsequent use. By embodying subsystem 25' and LDIP subsystem 122 within a single housing 121, an ultra-compact device is provided that can both dimension and identify packages moving along the package conveyor without requiring the use of any external peripheral input devices, such as tachometers, light-curtains, etc.

Second Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem

Referring now to Figs. 11 and 12, a unitary package identification and dimensioning system of the second illustrated embodiment 140 will now be described in detail.

As shown in Fig. 11, the unitary system 140 of the present invention comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 141, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 141 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 11, the unitary system comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacing as taught in copending US Application No. 09/327,756 filed June 7, 1999, supra; and International PCT Application No. PCT/US00/15624 filed December 7, 2000, incorporated herein by reference; (2) a PLIIM-based bar code symbol reading subsystem 25", shown in Figs. 6C1 through 6D5, for producing a 3-D scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and outputs from the unitary system; and (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions.

As shown in Fig. 11, the package imaging, detecting and dimensioning subsystem 122 comprises a number of subsystems integrated therewithin as shown, namely: a package velocity measurement subsystem 123, for measuring the velocity of transported packages by analyzing range data maps generated by the different scanning beams, using the inventive methods

disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000, incorporated herein by reference; a package-in-the-tunnel (PITT) indication subsystem 125, for automatically detecting the presence of each package moving through the scanning volume by reflecting a portion of one of the laser scanning beams across the width of the conveyor belt in a retro-reflective manner and then analyzing the return signal using first derivative and thresholding techniques disclosed in International Application No. PCT/US00/15624 filed December 7, 2000, published as WO 00/75856; a package (x-y) height/width/length dimensioning (or profiling) subsystem 124, integrated within subsystem 122, for producing x,y,z profile data sets for detected packages; and a package-out-of-the-tunnel (POOT) indication subsystem 125, integrated within subsystem 122, realized using predictive techniques based on the output of the PITT indication subsystem 125, for automatically detecting the presence of packages moving out of the scanning volume. As shown in Fig. 10, the unitary system 120 is adapted to receive data inputs from a number of input devices including, for example: weighing-in-motion subsystem 132 for weighing packages as they are transported along the conveyor belt; an RF-tag reading subsystem for reading RF tags on packages as they are transported along the conveyor belt; etc.

The low-resolution CCD camera 61 (having 640X640 pixels) in PLIIM subsystem 25'' is used to locate the x,y position of bar code labels on scanned packages using ambient illumination to form images on the low-resolution array 61A therewithin. When the low-resolution CCD area array 61A detects a bar code symbol on a package label, then the system controller 22 triggers the high-resolution CCD image detector 55A and the planar laser illumination arrays 6A and 6B so as to capture 2-D images of the high-resolution image detector's 3-D field of view 10'. The focal distance of the imaging subsystem of the high resolution image formation and detection module 55'' is controlled by package height coordinate information acquired by the LDIP subsystem 122. High-resolution scan data collected from 2-D image detector 55A is then decode processed to read the bar code symbol within the detected package label in a fully automated manner without human intervention. In all other respects, the unitary system 140 shown in Fig. 11 is similar to the system 120 shown in Fig. 9. By embodying subsystem 25'' and LDIP subsystem 122 within a single housing 141, an ultra-compact device is provided that can both dimension and identify packages moving along the package conveyor using a low-resolution CCD imaging device to detect package labels, and then use such detected label information to activate the high-resolution CCD imaging device 25'' to acquire images of the detected label for high performance decode processing.

Third Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem

In Fig. 13, a third illustrative embodiment of the unitary package dimensioning and identification system of the present invention 160 is shown mounted above a high-speed conveyor belt structure. As illustrated in Figs. 14A and 14B, unitary system 160 embodies the PLIIM subsystem 25' of Figs. 3E1-3E8 as well as the laser dimensioning and profiling (LDIP) subsystem 122 within a single housing 161 of compact construction. Unitary system 160 is

functionally identical to the unitary system 140 described above, expect that system 160 is packaged in the specially designed dual-compartment housing design shown in Figs. 14A, 14B, and 15 to be described in detail below.

As shown in Fig. 14A, the PLIIM subsystem 25" is mounted within a first optically compartment 162 formed in system housing 161 using optically opaque wall structures, whereas the LDIP subsystem 122 and beam folding mirror 163 are mounted within a second optically isolated compartment 164 formed therein below the first compartment 162. Both optically isolated compartments are realized using optically opaque wall structures well known in the art. As shown in Fig. 15, a first set of spatially registered light transmission apertures 165A1, 165A2 and 165A3 are formed through the bottom panel of the first compartment 162, in spatial registration with the transmission apertures formed 29A', 28', 29B' in subsystem 25". Below light transmission apertures 165A1, 165A2 and 165A3, there is formed a completely opened light transmission aperture 165B, defined by vertices EFBC, so as to allow laser light to exit and enter the first compartment 162 during system operation. A hingedly connected panel 169 is provided on the side opening of the system housing 161, defined by vertices ABCD. The function of this hinged panel 169 is to enable authorized personnel to access the interior of the housing and clean the glass windows provided over the light transmission apertures 29A', 28', 29B' in spatial registration with apertures 165A1, 165A2 and 165A3, respectively. This is an important consideration in most industrial scanning environments.

As shown in Figs. 14A, the LDIP subsystem 122 is mounted within the second compartment 164, along with beam folding mirror 163 directed towards a second light transmission aperture 166 formed in the bottom panel of the second compartment 164, in an optically isolated manner from the first set of light transmission apertures 165A1, 165A2 and 165A3. The function of the beam folding mirror 163 is to enable the LDIP subsystem 122 to project its dual amplitude-modulated laser beams 167 out of its housing, off beam folding mirror 163, and towards a target object to be dimensioned and profiled. Also, this light transmission aperture 166 enables reflected laser return light to be collected and detected off the illuminated target object.

Fig. 16 shows the unitary (PLIIM-based) package dimensioning and identification system of the third illustrative embodiment of the present invention. As shown, the various information signals are generated by the LDIP subsystem, and provided to the camera control (computer subsystem). The Camera Control Computer generates digital camera control signals which are provided to the image formation and detection (IFD subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either a image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user. The PLIIM subsystem" generates digital

images of the target object passing within the subsystem's field of view (FOV) and these images are then processed to decode bar code symbols represented within the images and produce package identification data. Each such package identification data element is then provided to the Camera Control Computer or other computer within the unit for linking with a corresponding package dimension data element, as described hereinabove. Optionally, acquired digital images of packages passing beneath the PLIIM subsystem 25'' can be processed in other ways to extract other relevant features of the package which might be useful in package identification, tracking, routing and/or dimensioning purposes.

Fig. 17 shows a fourth illustrative embodiment of the unitary package dimensioning and identification system of the present invention. As shown, this system embodies the PLIIM subsystem of the present invention as well as the laser dimensioning and profiling (LDIP) subsystem within a single housing of compact construction.

Fig. 18A shows the PLIIM subsystem and its components contained within a first optically isolated compartment formed the unitary system housing, and the LDIP subsystem contained within a second optically isolated compartment formed therein. A first set of spatially registered light transmission apertures is formed through the panels of both the first and second cavities to enable the PLIIM system to project its planar laser illumination beams towards a target object to be illuminated and collect and receive laser return light off the illuminated object. A second set of light transmission apertures. optically isolated from the first set of light transmission apertures, is formed in the second cavity to enable the LDIP subsystem to project its dual amplitude-modulated laser beams towards a target object to be dimensioned and profiled. and also to collect and receive laser return light reflected off the illuminated target object.

Fig. 18B shows the spatial layout of the various optical and electro-optical components mounted on the optical bench of the PLIIM subsystem installed within the first cavity of the system housing.

As shown in Fig. 18C, an illustrative implementation of the imaging subsystem contained in the image formation and detection (IFD) module employed in the PLIIM system of Fig. 17. comprises: a stationary lens system mounted before the stationary linear (CCD-type) image detection array; a first movable lens system for stepped movement relative to the stationary lens system during image zooming operations; and a second movable lens system for stepped movements relative to the first movable lens system and the stationary lens system during image focusing operations. The first movable lens system employs a zoom lens group translator to move the zoom lens group to a position specified by the Camera Control Computer shown in Fig. 20. The second movable lens system employs a focus lens group translator to move the focus lens group to a position specified by the Camera Control Computer shown in Fig. 20.

Fig. 19 shows a unitary (PLIIM-based) package dimensioning and identification system of the fourth illustrative embodiment. As shown therein, the various information signals are generated by the LDIP subsystem, and provided to the Camera Control (Computer) Subsystem. The Camera Control Computer generates digital camera control signals which are provided to the image formation and detection (IFD) subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly

reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either a image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user.

Fig. 20 illustrates the system architecture of the unitary (PLIIM-based) package dimensioning and identification systems of the third and fourth illustrative embodiments shown in Figs. 13 and 17. As shown therein, a Real-Time Package Height Profiling And Edge Detection Processing Module is employed within the LDIP subsystem (disclosed in copending US Patent No. 09/327,756 filed June 7, 1999 and International Application No. WO 00/75856 published 12/14/2000, each incorporated herein by reference in its entirety). The function of Real-Time Package Height Profiling And Edge Detection Processing Module is to automatically process raw data received by the LDIP subsystem and generate, as output, time-stamped data sets that are transmitted to the Camera Control (Computer) Subsystem. In turn, the Camera Control (Computer) Subsystem automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity.

Fig. 21 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem employed in the PLIIM-based systems shown in Figs. 13 and 17. As illustrated at Block A in Fig. 21, a row of raw range data collected by the LDIP subsystem is sampled every 5 milliseconds and received by the Real-Time Package Height Profiling And Edge Detection Processing Module. As indicated at Block B, the Real-Time Package Height Profiling And Edge Detection Processing Module converts the raw data set into range profile data R=f(int. phase), reference with respect to a polar coordinate system symbolically embedded in the LDIP subsystem, as shown in Fig. 23. The at Block C, the Real-Time Package Height Profiling And Edge Detection Processing Module uses geometric transformations to convert the range profile data set R[i] into a height profile data set h[i] and a position data set x[i]. At Block D, the Real-Time Package Height Profiling And Edge Detection Processing Module obtains current package height data values by finding the prevailing height using package edge detection without filtering, as taught in the method of Fig. 22. At Block E, the Real-Time Package Height Profiling And Edge Detection Processing Module finds the coordinates of the left and right package edges (LPE, RPE) by searching for the closest coordinates from the edges of the conveyor belt (x_a, x_b) towards the center thereof. At Block F, the Real-Time Package Height Profiling And Edge Detection Processing Module creates a time-stamped data set containing the following five information elements: the coordinate of the left package edge (LPE); the current

height value of the package (h); the coordinate of the right package edge (RPE); package velocity (V_b); and the time-stamp (nT). Notably, the belt/package velocity measure is obtained from the LDIP Package Dimensioner employing integrated velocity detection techniques described in copending US Application No. US Application No. 09/327,756 filed June 7, 1999, and International Application No. PCT/US00/15624, filed June 7, 2000, published by WIPO on December 14, 2000 under WIPO No. WO 00/75856 incorporated herein by reference in its entirety. Thereafter, at Block G, the Real-Time Package Height Profiling And Edge Detection Processing Module transmits the assembled data set to the Camera Control (Computer) Subsystem for processing and subsequent generation of real-time camera control signals that are transmitted to the Auto-Focus/Auto-Zoom Digital Camera Subsystem. These operation will be described in greater detail hereinafter.

Fig. 22 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Edge Detection Processing Method performed by the Real-Time Package Height Profiling And Edge Detection Processing Module at Block D in Fig. 21, each time a new raw range data set is received by the Real-Time Package Height Profiling And Edge Detection Processing Module, at a rate of about every 5 milliseconds or so in the illustrative embodiment.

Fig. 23 schematically illustrates the Real-Time Package Height Profiling Method carried out in the flow chart of Fig. 21, and the Real-Time Package Edge Detection Method carried out in the flow chart of Fig. 22. Notably, these processes are carried out for each sampled row of raw data collected by the LDIP subsystem and therefore, does not rely on the results computed by the computational-based package dimensioning processes carried out in the LDIP subsystem, described in great detail in copending US Application No. 09/327,756 filed June 7, 1999, and incorporated herein reference in its entirety.

Figs. 24A and 24B describe the Real-Time Camera Control Process that is carried out within the Camera Control Computer Subsystem employed within the PLIIM-based systems of Figs. 13 and 17. As illustrated in Figs. 24A and 24B, this control process has multiple threads that are carried out simultaneously each data processing cycle (i.e. each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem. As illustrated in this flow chart, the data elements contained in each received data set are automatically processed within the Camera Control (Computer) Subsystem in the manner described in the flow chart, and at the end of each data set processing cycle, generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity. Details of this control process will be described below.

As indicated at Block 24A, the camera control computer receives a time-stamped quintuple data set from the LDIP subsystem. This data set contains the following data elements: the coordinate of the left package edge (LPE); the current height value of the package (h); the

coordinate of the right package edge (RPE); package velocity (V_b); and the time-stamp (nT). The data elements associated with each current data set are initially buffered in a input row (i.e. Row 1) of the Package Data Buffer illustrated in Fig. 25. Notably, the Package Data Buffer functions like a five column first-in-first-out (FIFO) data element queue. As shown, each data element in the raw data set is assigned a fixed column index and (variable) row index which increments as the raw data set is shifted one index unit as each new incoming raw data set is received into the Package Data Buffer. In the illustrative embodiment, the Package Data Buffer has M number of rows, sufficient in size to determine the spatial boundaries of a package scanned by the LDIP subsystem using real-time sampling techniques which will be described in detail below

At Block B, the camera control computer analyzes the height data in the Package Data Buffer and detects the occurrence of height discontinuities, and based on such detected height discontinuities, determines the corresponding coordinate positions of the leading package edges specified by the left-most and right-most coordinate values (LPE and RPE) associated with the data set at this detected height discontinuity.

At Block C, the camera control computer determines the height of the package associated with the leading package edges determined at Block B above. At this stage in the control process, the camera control system, at Block D in Fig. 24A, analyzes the height values (i.e. coordinates) buffered in the Package Data Buffer, and determines the current height of the package. At this stage of the control process, numerous control "threads" are started, each carrying out a different set of control operations. As indicated in the flow chart of Figs. 24A and 24B, each control thread can only continue when the necessary parameters involved in its operation have been determined (e.g. computed), and thus the control process along a given control thread must wait until all involved parameters are available before resuming its ultimate operation (e.g. computation of a particular intermediate parameter, or generation of a particular control command), before ultimately returning to the start Block A, at which point the next time-stamped data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module. Notably, such data set input operations are carried out every 5 milliseconds in the illustrative embodiment, and therefore updated camera commands will be generated and provided to the auto-focus/auto-zoom camera at substantially the same rate, to achieve real-time adaptive camera control performance required by demanding imaging applications.

As indicated at Blocks E, F, G H, I, A in Figs. 24A and 24B, a first control thread runs from Block D to Block A so as to reposition the focus and zoom lens groups within the Auto-Focus/Auto-Zoom Digital Camera Subsystem each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module. As indicated at Block E, the camera control computer uses the Focus/Zoom Lens Group Position Lookup Table in Fig. 27 to determine the focus and zoom lens group positions based which will capture focused digital images having constant dpi resolution, independent of detected package height. This operation requires using the detected height value determined at Block D and looking up the corresponding focus and zoom lens group positions listed in the Focus/Zoom Lens Group Position Lookup Table. At Block F, the camera control computer translates the obtained transmits the determined focus and zoom lens group positions into lens group movement

commands which are transmitted to the lens group position translators employed in the auto-focus/auto-zoom camera subsystem. Then at Block G, the camera control computer checks the resulting positions achieved by the lens group position translators, responding to the transmitted commands, and then at Blocks H and I, the camera control computer automatically corrects the lens group positions which are required to capture focused digital images having constant dpi resolution, independent of detected package height. As indicated at by the control loop formed by Blocks G, H, I G, the camera control computer will correct the lens group positions until focused images are captured with constant dpi resolution, independent of detected package height, and when so achieved, automatically returns this control thread to Block A shown in Fig. 24A.

As indicated at Blocks J, K, L, A in Figs. 24A and 24B, a second control thread runs from Block D in order to determine and set the optimal photo-integration time period ($\Delta T_{photo-integration}$) parameter which will ensure that digital images captured by the Auto-Focus/Auto-Zoom Digital Camera Subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1) required by typical image-based bar code symbol decode processors and OCR processors. As indicated at Block J, the camera control computer analyzes the current height value in the Data Package Buffer, and determines the speed of the package (V_b). At Block K, the camera control computer uses the computed values of average package height, speed (V_b) and the Photo-Integration Time Look-Up Table of Fig. 29, to determine the photo-integration time parameter ($\Delta T_{photo-integration}$) which will ensure that digital images captured by the Auto-Focus/Auto-Zoom Digital Camera Subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1). At Block L, the camera control computer generates a digital photo-integration time control signal based on the photo-integration time parameter ($\Delta T_{photo-integration}$) found in the Photo-Integration Time Look-Up Table, and sends this control signal to the CCD image detection array employed in the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD Module). Thereafter, this control thread return to Block A as indicated in Fig. 24A.

As indicated at Blocks D, M, N, O, Q in Figs. 24A and 24B, a third control thread runs from Block D in order to determine the pixel indices (i,j) of a selected portion of a captured image which defines the region of interest (ROI) on a package bearing package identifying information (e.g. bar code label, textual information, graphics, etc.), and to use these pixel indices (i,j) to produce image cropping control commands which are sent to the Auto-Focus/Auto-Zoom Digital Camera Subsystem. In turn, these control commands are used by the Auto-Focus/Auto-Zoom Digital Camera Subsystem to crop pixels in the ROI of captured images, and to transfer these cropped images to image-based bar code symbol decoder and/or OCR processor for subsequent processing. This ROI cropping function serves to selectively transmit only those image pixels within the Camera Pixel Buffer of Fig. 26, having pixel indices (i,j) which spatially correspond to the (row,column) indices in the Package Data Buffer of Fig. 25. As indicated at Block M, the camera control computer transforms the position of left and right package edge (LPE, RPE) coordinates (buffered in the row the Package Data Buffer at which the height value was found at Block D), from the local Cartesian coordinate reference system symbolically embedded within the LDIP subsystem shown in Fig. 23, to a global Cartesian

coordinate reference system embedded within the center of the conveyor belt structure, beneath the LDIP subsystem, also shown in Fig. 23. Such coordinate frame conversions can be carried out using homogeneous transformation well known in the art.

At Block N in Fig. 24B, the camera control computer detects the boundary coordinates of the package based on the spatially transformed coordinate values of the left and right package edges (LPE,RPE) buffered in the Package Data Buffer. Based on the detected package boundary coordinates determined Block N, the camera control computer determines the corresponding pixel indices (i,j) which specifies the portion of the image frame (i.e. a slice of the region of interest), to be effectively cropped from the image to be subsequently captured by the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD subsystem). Then, this control thread dwells at Block Q until the other control threads terminating at Block Q have been executed, providing the necessary information to complete the operation recited at Block Q.

As indicated at Block P, the camera control computer uses the package time stamp (nT) contained in the data set being currently processed by the camera control computer, as well as the package velocity (V_b) determined at Block J, to determine the "Start Time" of Image Frame Capture (STIC). The reference time is established by the package time stamp (nT). The Start Time when the image frame capture should begin is measured from the reference time, and is determined by (1) predetermining the distance Δz measured between (i) the local coordinate reference frame embedded in the LDIP subsystem and (ii) the local coordinate reference frame embedded within the Auto-Focus/Auto-Zoom Camera Subsystem, and dividing this predetermined (constant) distance measure by the package velocity (V_b) determined at Block J. Then at Block Q, the camera control computer uses the Start Time of Image Frame Capture determined at Block P to generate a command for starting image frame capture, and uses the pixel indices (i,j) determined at Block O to generate commands for cropping the corresponding slice (i.e. section) of the region of interest in the image to be or being captured and buffered in the Image Buffer within the IFD Subsystem (i.e. Auto-Focus/Auto-Zoom Digital Camera Subsystem). Then at Block R, these real-time "image-cropping" commands are transmitted to the Auto-Focus/Auto-Zoom Digital Camera Subsystem, and the control process returns to Block A to begin processing another incoming data set received from the Real-Time Package Height Profiling And Edge Detection Processing Module. This inventive control operation reduces the transmission of image pixels to the bar code symbol decoder and/or OCR processor which do not contain information about the identity, origin and/or destination of the package moving along the conveyor belt.

Notably, by using the real-time camera control process described above, the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. IFD module) driven by the camera control computer can perform numerous functions in a piece-meal manner while operating on only one data set from the LDIP Subsystem at a time.

Fig. 26. illustrates the structure of the Camera Pixel Data Buffer employed by the Auto-Focus/Auto-Zoom Digital Camera Subsystem shown in Fig. 20. As shown, each pixel element in each captured image frame is stored in a storage cell of the Camera Pixel Data Buffer, assigned a unique set of pixel indices (i,j).

Fig. 27 shows an exemplary Zoom and Focus Lens Group Position Look-Up Table associated with the Auto-Focus/Auto-Zoom Digital Camera Subsystem and which is used by the Camera Control (Computer) Subsystem of the illustrative embodiment. For a given package height detected by the Real-Time Package Height Profiling And Edge Detection Processing Module, the Camera Control Computer (at Block E in Fig. 24B) uses the Look-Up Table to determine the precise positions to which the focus and zoom lens groups must be moved by generating and supplying real-time camera control signals to the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity.

Fig. 28 shows a graphical plot of the focus and zoom lens movement characteristics associated with the zoom and lens groups employed in the illustrative embodiment of the Auto-Focus/Auto-Zoom Digital Camera Subsystem. Notably, these characteristics were used to generate the Zoom and Focus Lens Group Position Look-Up Table of Fig. 27. As shown in this graphical chart, for a given detected package height, the position of the focus and zoom lens group relative to the Camera's working distance is obtained by finding the points along these characteristics at the specified working distance (i.e. detected package height).

Fig. 29 shows an exemplary Photo-integration Time Period Look-Up Table associated with CCD image detection array employed in the Auto-Focus/Auto-Zoom Digital Camera Subsystem of the PLIIM-based system. As shown at Block K in Fig. 24B, for a given detected package height and package velocity, the Camera Control Computer uses this Look-Up Table to determine the precise photo-integration time period for the CCD image detection elements employed within the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity.

Fig. 30 shows a four-sided tunnel-type package identification and dimensioning (PID) system that has been constructed by arranging four PLIIM-based PID units shown in Figs. 13 and 17 about a high-speed package conveyor belt subsystem. In this system, the LDIP subsystem in the top PID unit is configured to dimension packages transported along the belt, while the bottom PID unit is arranged to view packages through a small gap between conveyor belt sections, and all of the PID units are operably connected to the Ethernet control hub of a local area network (LAN). Fig. 31 shows the tunnel-type system of Fig. 30 embedded within a first-type LAN having a Ethernet control hub. Fig. 32 shows the tunnel-type system of Fig. 30 embedded within a second-type LAN having a Ethernet control hub and a Ethernet data switch.

Applications Of The Unitary Package Identification And Dimensioning System Of The Present Invention

In general, the package identification and measuring systems of the present invention can be installed in package routing hubs, shipping terminals, airports, factories, and the like. There of course will be numerous other applications for such systems as new situations arise, and the capabilities of such systems become widely known to the general public.

Modifications Of The Illustrative Embodiments

While each embodiment of the PLIIM system of the present invention disclosed herein has employed a pair of planar laser illumination arrays, it is understood that in other embodiments of the present invention, only a single PLIA may be used, whereas in other embodiments three or more PLIAs may be used depending on the application at hand.

While the illustrative embodiments disclosed herein have employed electronic-type imaging detectors (e.g. 1-D and 2-D CCD-type image sensing/detecting arrays) for the clear advantages that such devices provide in bar code and other photo-electronic scanning applications, it is understood, however, that photo-optical and/or photo-chemical image detectors/sensors (e.g. optical film) can be used to practice the principles of the present invention disclosed herein.

While the package conveyor subsystems employed in the illustrative embodiments have utilized belt or roller structures to transport packages, it is understood that this subsystem can be realized in many ways, for example: using trains running on tracks passing through the laser scanning tunnel; mobile transport units running through the scanning tunnel installed in a factory environment; robotically-controlled platforms or carriages supporting packages, parcels or other bar coded objects, moving through a laser scanning tunnel subsystem.

While the various embodiments of the package identification and measuring system hereof have been described in connection with linear (1-D) and 2-D code symbol scanning applications, it should be clear, that the system and methods of the present invention are equally suited for scanning alphanumeric characters (e.g. textual information) in optical character recognition (OCR) applications, as taught in US Patent No. 5,727,081 to Burges, et al. incorporated herein by reference, and scanning graphical images as practiced in the graphical scanning arts.

It is understood that the laser scanning systems, modules, engines and subsystems of the illustrative embodiments may be modified in a variety of ways which will become readily apparent to those skilled in the art, and having the benefit of the novel teachings disclosed herein. All such modifications and variations of the illustrative embodiments thereof shall be deemed to be within the scope and spirit of the present invention as defined by the Claims to Invention appended hereto.